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4TH QUARTER 1955

Electrical REVIEW

ALLIS-CHALMERS
Electrical REVIEW

THE COVER

HARNESSED TO THE WHITE RIVER, this team of four identical Francis-turbine-driven generators, each rated 42,100 kva at 128 rpm, is converting water power to electric power at Bull Shoals Dam and helping to speed the economic development of adjacent areas.* Designed for expansion, the powerhouse at this multi-purpose dam is large enough to accommodate four additional units. Although installation started in 1952 and these units have been generating power since 1953, head conditions approaching normal were not reached until 1955.

An article describing modern hydraulic turbines starts on page 20. Another article, starting on page 4, describes hydro-generator excitation systems. Bull Shoals generators shown on the cover have main and pilot exciters with indirect-acting voltage regulators.

(Army Engineers Photo)

* *The Bull Shoals plant is a unit of a Corps of Engineers' multi-purpose dam project, designed, constructed, and operated under the direction of the Little Rock District Engineer.*

Allis-Chalmers

ELECTRICAL REVIEW

Vol. XX No. 4

Issued quarterly. Subscription rates: U. S., Mexico, and Canada, $2.00 per year; other countries, $3.00; single copies, $1.00 in advance.

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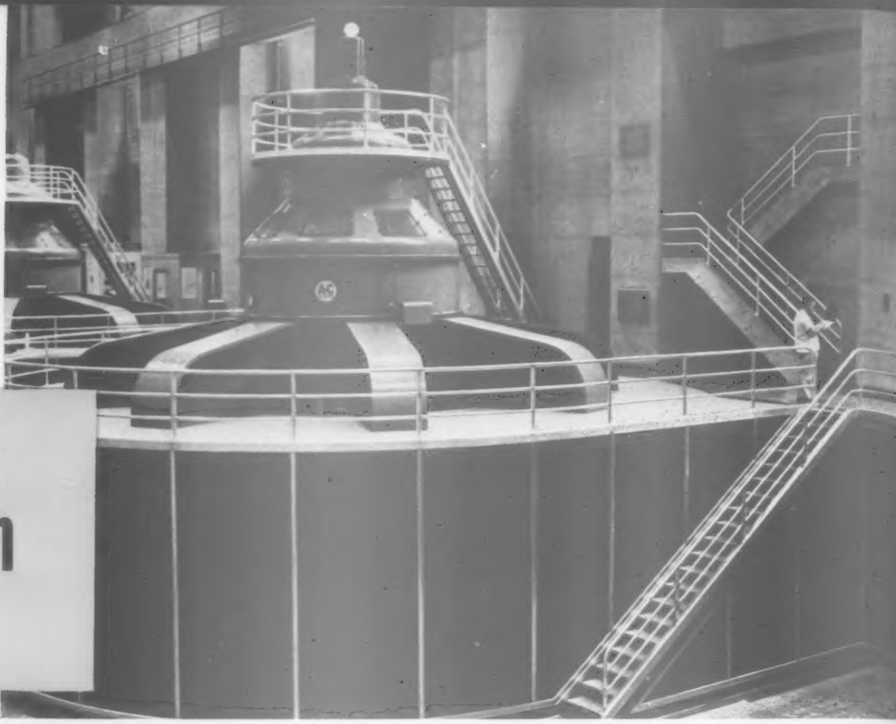
Indexed regularly by Engineering Index, Inc.
Allis-Chalmers ELECTRICAL REVIEW is available to public and institutional libraries on microfilm from University Microfilms, 313 N. First St., Ann Arbor, Mich.

Address Allis-Chalmers Electrical Review, Milwaukee 1, Wisconsin

Printed in U. S. A.

Selecting Excitation Systems



MODERN HYDRO-GENERATORS have exciter and pilot exciter mounted above the main generator. *(U.S. Bureau of Reclama*

FOR HYDRO-GENERATORS

by **H. H. ROTH**
Motor and Generator Dept.
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Choice of excitation system should be made only after a careful analysis of the particular hydro-generator involved.

GENERATOR EXCITATION SYSTEMS for hydro-turbine generators have grown in complexity as hydro stations and interconnected systems have increased in size and capacity.

Hand-operated shunt field rheostat control was adequate for self-excited direct current generators used in small early stations to develop power for local consumption. Excitation requirements of early ac plants were also quite simple.

Exciters were usually either direct connected or belt driven from the generator shaft. As generating units became larger and multi-unit plants were built, the excitation bus came into common use. It supplied current at a constant voltage for field excitation of all the machines in the station. Separate generator field rheostats for each machine provided excitation control. Exciters supplying power to the excitation bus were separate machines driven by their own hydraulic turbines. An early hydroelectric plant using this system is shown in Figure 1.

Further growth of power systems and the increasing size of generating units required the development of modern generator excitation control systems.

The excitation system of an alternating current generator consists of all the equipment necessary to supply and regulate the generator field current. This field current is regulated to maintain the generator output voltage at a desired value under varying operating conditions.

In modern excitation systems, a separate main exciter is provided for each generator. However, the other components of the excitation system can differ considerably, depending upon the size and speed of the generator, and the type of voltage-regulating equipment selected.

Generator rating influences excitation system

Today, relatively small high speed hydro-generator units are usually equipped with direct-connected main exciters and direct-acting generator voltage regulators. No pilot exciter is used.

A direct-acting regulator has both the voltage-sensing element and the regulating resistance built into a single, complete unit. Regulators of this type have limited current capacity and can therefore be applied only to exciters requiring relatively small shunt field current — usually under about 25 amperes. A typical *Rocking Contact* direct-acting voltage regulator is shown in Figure 2.

Self-excited main exciters, having excitation voltages that vary with output voltage, permit the use of physically small resistance elements which can be accommodated in direct-acting regulators. When direct-acting voltage regulators are applied, generator field rheostats are frequently used. This permits stable generator operation even at light loads, since the exciter can be operated at a sufficiently high voltage to assure its stability.

Direct-acting regulators, however, have only limited application even on small machines if pilot exciters are used. Main exciters that receive their excitation from a constant voltage source, such as a pilot exciter, require a much larger range of regulating resistance than can be built into a direct-acting regulator.

When determining whether a direct or indirect-acting regulator should be applied, the main exciter field current handled by the regulator is the principal factor to be considered. In Figure 3, the line approximately dividing small high speed generators to which direct-acting regulators should be applied from larger low speed units requiring indirect-acting regulators is primarily a function of the main exciter field current.

An indirect-acting voltage regulator, shown in Figure 4, is one in which the voltage-sensing element does not vary the regulating resistance directly. Instead, the resistance element is a motor-operated main exciter field rheostat. Relatively slow in operation, this rheostat cuts resistance in or out of the main exciter field circuit upon a signal from the voltage-sensing element.

While this action assures sufficiently fast regulation for small voltage changes, field forcing is provided for large changes. This is accomplished by two high speed contactors: a "raise" contactor to short-circuit a portion of the regulating resistance, and a "lower" contactor to insert additional resistance.

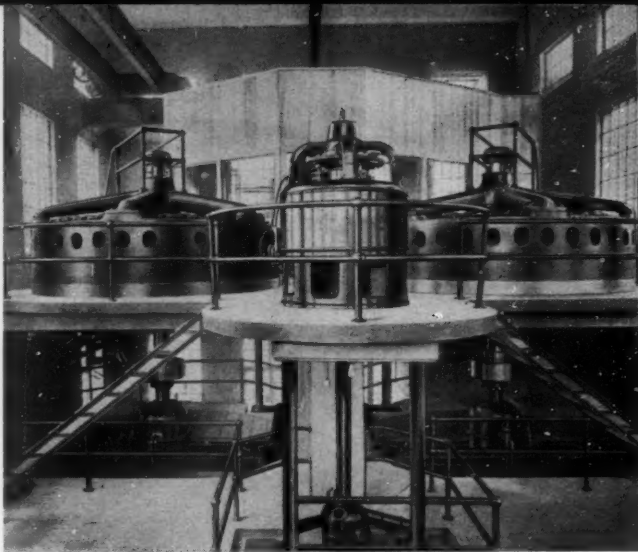
Upon a drop in generator terminal voltage, the "raise" contactor closes. This decreases the effective resistance in the exciter field circuit and maintains increased generator excitation until the motor-operated exciter field rheostat can move into the correct position for the new requirement. Should generator terminal voltage go up, the "lower" contactor closes, inserting additional resistance in the main exciter field. The closed position is maintained until the motor-operated rheostat can adjust itself to the new operating condition.

Rate of response built into exciters

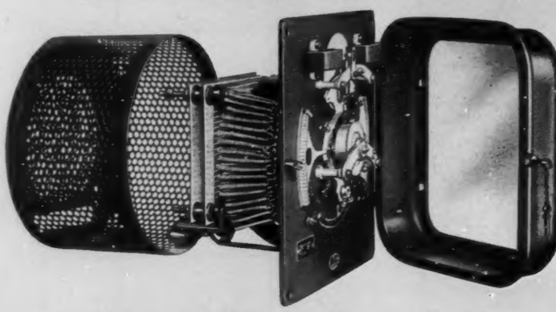
Since hydroelectric units are slow speed machines as compared to turbogenerators, no difficulty is experienced in building direct-connected main and pilot exciters of any required capacity. These slow speed exciters are very reliable and make each machine an independent generating unit.

Unless otherwise specified, main exciters are normally built with a 0.5 rate of response. Exciter response is the rate of increase or decrease of the main exciter voltage when resistance is suddenly removed from, or inserted in, its shunt field. The method of determining exciter response is illustrated in Figure 5.

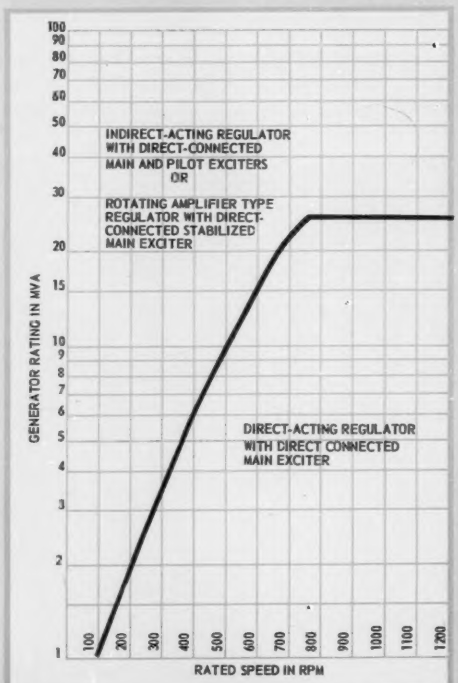
First, a build-up curve showing the exciter voltage as a function of time is plotted. Required information is obtained from an oscillogram showing the build-up of exciter voltage, starting at the nominal collector ring voltage of the generator served by the particular exciter involved. Next, a straight line, starting at nominal collector ring voltage for the ac machine and contained within the limits of zero to 0.5 seconds elapsed time, is drawn across the build-up curve. It is drawn so that the area between the curve and the straight line below the point of intersection



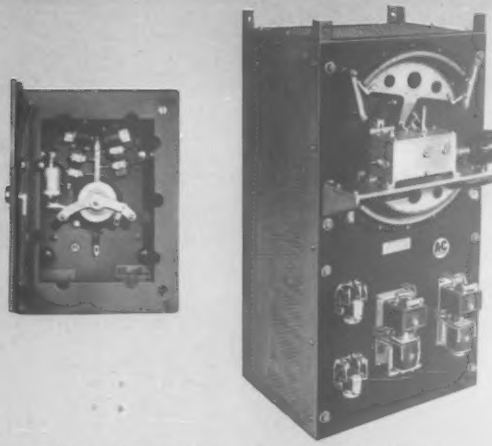
IN 1909, when these units were installed, accepted practice required separate exciters (unit in foreground), driven by their own individual hydraulic turbines. **(FIGURE 1)**



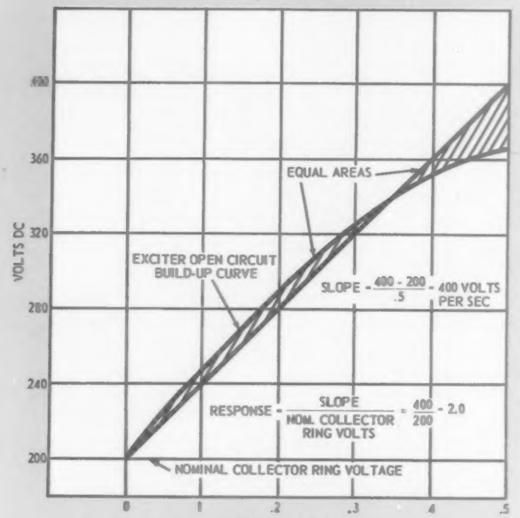
A ROCKING CONTACT sector inserts or removes self-contained resistance elements as required by voltage-sensing torque motor of this direct-acting regulator. **(FIGURE 2)**



FOR GENERATOR RATINGS below and to the right of this curve, direct-acting regulators are normally applied; other ratings generally require indirect-acting or rotating-amplifier type regulators. **(FIG. 3)**



TYPICAL of indirect-acting voltage regulators, this unit has voltage-sensing element (left), which sends signal to motor-driven resistance element (right), to increase or decrease resistance in excitation circuit. (FIGURE 4)



HOW the response of an exciter designed for the unusually high response of 2.0 was determined is indicated by these curves. (FIG. 5)

MODERN 37,500-kva, 164-rpm unit in the foreground has direct-connected main and pilot exciters. Four 20,000-kva units in background, originally installed in 1916, have been modernized with belt-driven pilot exciters. (FIGURE 6)

is the same as the area contained within these lines above the point of intersection.

The straight line is the average slope of the build-up curve in volts per second. This slope, divided by the nominal collector ring voltage, is the nominal response of the exciter. Since the slope of the build-up curve will change as nominal collector ring voltage changes, nominal response of a given exciter changes with any change in nominal collector ring voltage of the ac machine. For example, the curves in Figure 5 are based on a collector ring voltage of 200 volts. If, however, this exciter is applied to an ac machine requiring 250 volts nominal excitation, the exciter response ratio will be lower. In the latter case, the average slope would be determined from a point starting at 250 volts, where the build-up is less rapid, as can be seen by referring to Figure 5.

Exciter response, however, is only one of several factors which determine actual response of an ac generator to any sudden change in system voltage. Exciter response merely determines how quickly the exciter tends to increase or decrease the excitation voltage of the generator upon a signal from the voltage regulator. Response of the generator to a change in its excitation is a different matter. The speed at which a voltage regulator acts to change excitation voltage, the open-circuit time constant, and the transient reactance of the generator are all of importance.

For machines having a high transient reactance, a higher nominal exciter response will not greatly improve the overall response of the unit. The greatest improvement from high exciter response is obtained with machines having either a low transient reactance or a short time constant.

Exciters having a response higher than 0.5 can be furnished, but they always require the use of a separate source of main exciter excitation, such as a pilot exciter. Where main exciters are separately excited, indirect-acting generator voltage regulators must be used.

Most of the larger modern units use direct-connected main and pilot exciters. In Figure 6, the foreground unit is typical of a modern installation, while the 20,000-kva machines in the background, built in 1916, originally had direct-connected main exciters only. They were later modernized by adding pilot exciters. Since the original design did not provide for pilot exciter mounting on the main exciters, V-belt drives were used, and the pilot exciters were mounted on brackets located on the main exciter field yokes.

Modern excitation systems offer many variations

In some excitation systems the pilot exciter is omitted and the station battery is used for excitation of the main exciter. Figure 7 shows a unit employing this arrangement. The motor-generator set used for battery charging actually becomes the pilot exciter, while the station battery floats on the circuit for emergency use. Since this scheme is essentially an excitation system having both a main exciter and pilot exciter, the voltage regulator employed is identical to that used in a conventional pilot exciter system.

Rotating amplifier exciters are new for hydros

In recent years, the rotating-amplifier type voltage regulator has been developed. Initially intended for use with

large turbogenerators, it has several advantages not obtainable with the rheostatic-type regulator, and its application has been extended to include hydroelectric units.

The principal advantage of rotating-amplifier regulators over rheostatic regulators usually is that minimum excitation can be maintained automatically, although the improved speed of response is sometimes an important advantage. Under light system loading system power factor may approach unity, or even become leading. An increase in system voltage resulting from this high power-factor operation may cause the generator voltage regulator to reduce generator excitation to a point below that required for stable operation. Under this condition, the generator may become unstable and pull out of synchronism when a system disturbance occurs.

Rotating-amplifier voltage regulators, because of the minimum excitation feature, automatically integrate the excitation requirements of the generator for the load being carried at any operating voltage. Generator field current never drops below the stable point.

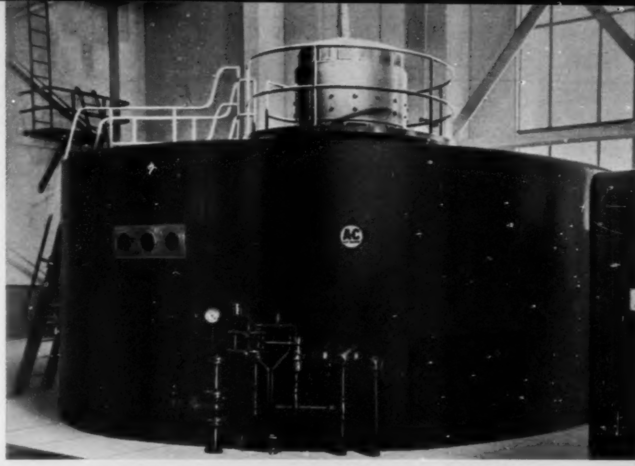
To insure operating stability under light load condition, the main exciter used with this system is stabilized. (A stabilized exciter is one which will maintain a steady voltage when operated self-excited at low voltages which may be as low as 20 percent of rated voltage.) This stability requirement may mean the use of an exciter physically larger and somewhat more costly than a separately excited exciter.

Shown in Figure 8 are the components of a *Regulex* rotating amplifier used for generator excitation control. All of the static control elements are contained in the control cabinet. A comparator circuit contained in this cubicle compares the generator output voltage with a reference voltage. When the generator output voltage requires adjustment, the circuit sends a signal to the *Regulex* rotating amplifier to either increase or decrease its output. Connected in series with the field circuit of the self-excited main exciter, the output of the *Regulex* generator serves to buck or boost the self-excited field as required by the generator voltage.

For generating units of medium or large size, the use of direct-connected main and pilot exciters with an indirect-acting rheostatic voltage regulator will result in a slightly lower first cost than a stabilized main exciter and rotating-amplifier voltage-regulating equipment. Maintenance requirements, however, will be lower with the rotating-amplifier voltage control system, since it has no moving parts such as contactors and relays. The only wearing parts are the commutator, brushes, and bearings of the rotating amplifier motor-generator set.

Overvoltage protection must be provided

Voltage regulators on hydroelectric units using direct-connected main and pilot exciters must be provided with pilot exciter overvoltage protection. All hydroelectric units are subject to overspeed conditions. Governor failure coinciding with a sudden loss of load may permit a unit to reach full runaway speed. Should the generating unit overspeed, the voltage of the pilot exciter will increase in proportion to the speed increase, since the pilot exciter, which is a flat compound-wound machine, operates at fixed excitation



DIRECT-CONNECTED main exciter only is used on this 27,500-kva, 400-rpm generator. Station battery energizes main exciter field. **(FIG. 7)**

under the control of a manually operated shunt field rheostat. This increase in voltage further increases excitation of the pilot exciter. At full runaway speed, the pilot exciter voltage may attain a value as high as 275 percent of normal.

The main exciter, partially as a result of its increase in speed and partially as a result of its increased excitation voltage, also greatly increases its voltage output. The main generator excitation is thereby increased, and the generator voltage may reach a value higher than the normal dielectric test voltage of its stator windings.

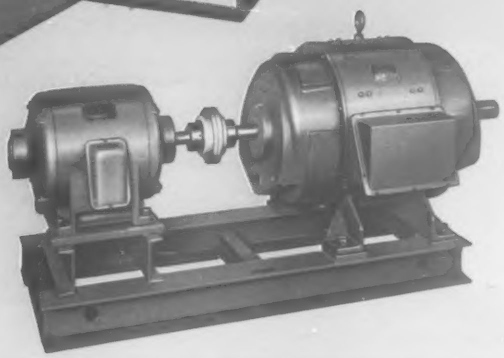
During overspeed operation, the generator voltage regulator attempts to hold the generator voltage to normal. However, because of the cumulative effects of higher speed, higher pilot exciter voltage, and higher main exciter voltage, sufficient regulating resistance does not exist within the regulator itself to hold the generator voltage to a safe value. To guard against this condition, pilot exciter voltage is usually limited by a voltage relay to a value which affords complete protection to the exciters and to the generator. When pilot exciter voltage increases, this relay opens a set of contacts and inserts resistance in the pilot exciter field circuit. This additional resistance, an amount sufficient to hold the pilot exciter output voltage to a very low value, enables the voltage regulator to retain control.

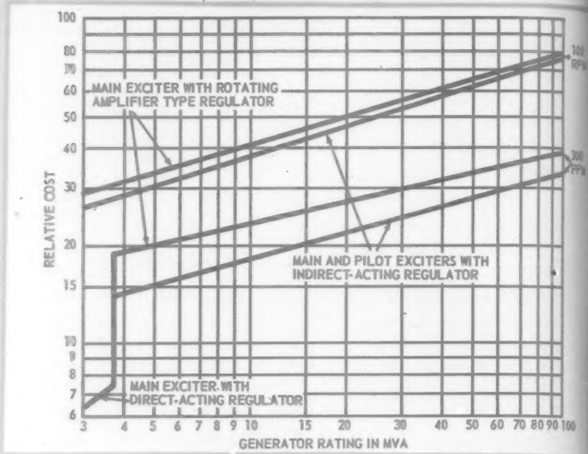
Generator/motors pose excitation problem

The field of hydroelectric generation now includes reversible pumped-storage units. In general, the excitation systems for reversible generator/motors are identical with those of standard generators, except for certain additional requirements. The generator/motor of a pumped-storage unit must be capable of operating in either direction of rotation, and the exciters must be designed for this service. Since the polarity of the exciters will reverse with a change in the direction of rotation, instruments used in the excitation system, such as voltmeters and ammeters, have zero center scales.

When starting a large reversible generator/motor as a motor, system requirements may make it desirable to start the unit by means of synchronous starting. This starting method requires a generating unit which can be isolated from the system and electrically connected to the pumped-storage unit at standstill. Field current is then applied to both machines, and the generating unit started. The two

MINIMUM EXCITATION can be maintained automatically by rotating-type regulators, such as the *Regulex* generator voltage regulator. All static components are contained in cubicle. The *Regulex* generator bucks or boosts the self-excited main exciter field as required to maintain constant generator output voltage. **(FIGURE 8)**





APPROXIMATE relative cost of rotating and indirect-acting mechanical regulators for a given size hydro-generator can be determined from these curves. **(FIG. 9)**

units are brought up to speed together and synchronized with the system.

This method of starting requires a source of excitation for both machines when they are at a standstill. Obviously, for such installations a motor-generator exciter set replaces the usual exciters and must be large enough to furnish excitation for both machines during the starting period. The voltage-regulating equipment is the same as for machines used only as generators.

Most hydroelectric plants also have a spare exciter set for use if the direct-connected exciter should fail. This spare exciter is usually a motor-generator set of sufficient capacity to serve any generator in the station. Normally provided with its own voltage regulator, this exciter set may be switched to any generator in the station. The use of a separate voltage regulator is desirable, since the motor-generator set will usually operate at a much higher speed than the direct-connected exciters, and the characteristics of the two exciters therefore differ considerably.

New ac exciter may find application

A recent development in exciters is the ac excitation system consisting of an inductor alternator, a rectifier, and a static control element. In this system, the exciter output voltage is varied by means of a magnetic amplifier connected to the terminals of an ac exciter. The magnetic amplifier, under the control of a voltage-sensitive static control element, acts as a variable-reactance load. This variable load is added to the load imposed on the exciter by the main generator field requirements to maintain required excitation voltage.

Inductor alternator characteristics make the voltage output of this type exciter very sensitive to the power factor of its load. Varying the power factor of the exciter load by means of a magnetic amplifier varies its output voltage over a very wide range. This characteristic is used to control the exciter voltage, with resulting voltage control of the generator.

This system was developed primarily for use on large two-pole turbogenerators where commutation problems limit the capacity of direct-connected exciters. The inductor alternator, having no commutator, may be built in any rating required for direct connection. While this excitation system could be applied to hydroelectric units, conventional low speed direct-connected exciters for hydro units have proved very reliable and can be built in any size. Consequently, this new excitation system has not been applied to hydroelectric units, but there may be advantageous applications in the future.

What about cost?

In any excitation system the main exciter represents the greater part of the investment. Both exciter and regulator costs, for generators of the same kva rating, vary inversely with the speed of the unit. While precise figures for the various systems are somewhat difficult to express in general terms, the relative investment required for the two types of excitation systems most generally used on large units is indicated in Figure 9.

Items included in this comparison are: main exciter, pilot exciter when used, and the type voltage regulator indicated. Only two unit speeds, 100 and 300 rpm, are considered. For a 300-rpm unit the rotating-amplifier control system with a direct-connected main exciter is more expensive than an indirect-acting rheostatic voltage regulator with direct-connected main and pilot exciters. For 100-rpm units, this cost differential is substantially reduced and almost disappears at the higher kva ratings. This results from the greater saving obtained by eliminating the pilot exciter, which becomes more costly as machine speed is reduced.

To accurately determine the preferred excitation system for any particular hydro-generator installation, an analysis of both function and cost should be made for the proposed installation. In some cases, especially if higher than normal exciter response is required, the rotating-amplifier excitation system may prove the most economical.

ANNEALING LINE incorporates many interesting heating, drive, and control problems that have been solved through teamwork of engineers representing the steel mill, builders of heavy mill equipment, and manufacturers of associated electrical equipment.

Controlling Processing Lines FOR TRANSFORMER STEEL


by **E. F. BOENING**
Control Section
Allis-Chalmers Mfg. Co.

and

JOHN KOSTELAC
Electrical Department
Crucible Steel Co. of America
Midland, Pennsylvania

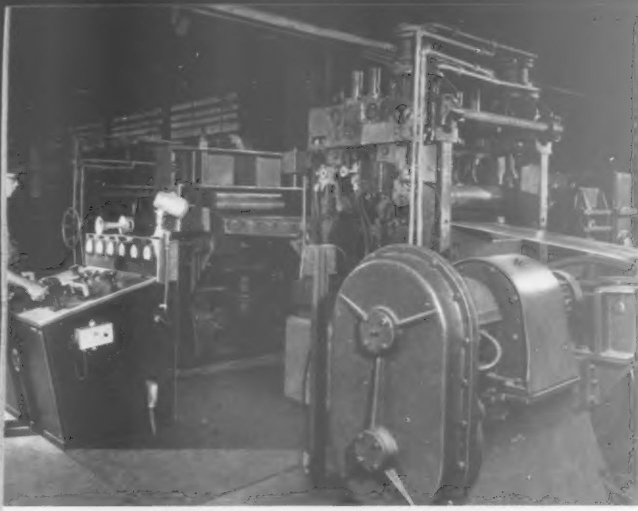
Magnetic-amplifier controls are now playing an important part in production of quality transformer core steel.

A RAPIDLY INCREASING DEMAND for greater quantities of transformer core steel has resulted in the installation of new processing lines designed primarily for handling grain-oriented silicon steel at Crucible Steel's Midland Works. Additional finishing lines are being added at Allis-Chalmers Pittsburgh Works to handle the semi-processed steel from this new mill. The large variety of both ac and dc motors and their associated equipment in these lines — such as high and low voltage switchgear, motor control centers, operating control stations and control boards — present an interesting problem of coordination. The control of special drives is the key to overall coordination.

Process lines coordinated

After a heat of special transformer steel has been processed to the point where it is in the form of a hot strip, it is ready for cleaning to remove surface scale. In a typical installation, the scale is removed by running the strip through long sulfuric acid pickling tanks. Figure 1 shows the entry section of the pickling line and Figure 2 shows the delivery section control panel.

After this pickling process, the coil is ready for the first cold reduction. Following the first cold-rolling operation, the strip is passed through a horizontal gas-fired furnace having a controlled atmosphere. This process is called bright annealing because it produces clean, bright, oxide-free surfaces and thereby eliminates subsequent pickling operations. After annealing, the strip is ready for the second cold operation for reduction to final gauge. Since cold-reduction introduces additional stresses into the steel, the coil must be returned to the annealing line for further annealing. After the second annealing, the coil is ready for shipment as semi-processed steel. However, in some cases the coil may be run through a process line for welding,



PICKLING LINE entry section has uncoiler, leveler, and shear for handling new coils brought to the line for cleaning. **(FIGURE 1)**

COMPLETELY STATIC, amplifiers (left) provide current-limit acceleration and deceleration plus *IR* drop compensation. **(FIGURE 2)**

side trimming, shearing, and inspection purposes before shipment.

At Pittsburgh the strip may undergo additional procedures before it is made into finished transformer cores. However, in any case the strip must undergo a high temperature anneal employing a controlled atmosphere to develop its magnetic properties to the fullest extent. In one procedure following the high temperature anneal, a continuous heat-flattening line having a gas-fired catenary-type furnace is used to remove coil set. In the same line an inorganic insulating coating is applied to the strip.

In all of these processing lines extremely sensitive controls are required at each step. Magnetic-amplifier control was chosen for its reliability as well as its sensitivity. Details of the processing steps will show the coordination of the control equipment.

Pickling line controlled

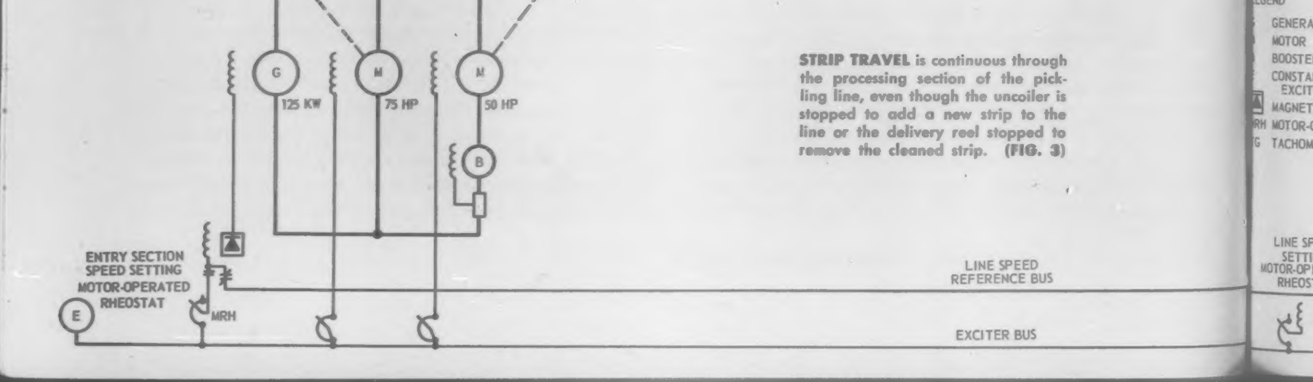
Representative of the processing line control equipment is the pickling line, shown schematically in Figure 3. The continuous pickling line consists of three sections.

Entry section

Equipment for handling and charging the coil into the line is located at the entry section. Here also is the processor, or leveler, which flattens the steel by means of a series of rolls. In the entry section of the line, the head end of a coil is joined to the tail end of the preceding coil. A shear is located after the leveler to square the ends of the strip for joining. The strip ends are joined by either riveting or welding.

Process section

In the processing section the oxide on the strip is removed mechanically and chemically. The strip first passes through the *wheelabrator* machine and then through the acid tanks. The *wheelabrator* machine throws abrasive at the moving strip to remove scale — a process similar to sand blasting. This mechanical process reduces the number of acid tanks required by substantially aiding the pickling action. After passing through the *wheelabrator* machine, the strip slides into the acid tanks which clean the strip of all oxides. Following this process are the high pressure sprays, the



STRIP TRAVEL is continuous through the processing section of the pickling line, even though the uncoiler is stopped to add a new strip to the line or the delivery reel stopped to remove the cleaned strip. **(FIG. 3)**

hot rinse tanks which remove the acid carryover, and the dryer.

Delivery section

At the delivery section the strip is side trimmed, if required, and sheared at proper intervals to form individual coils. A scrap chopper is used in conjunction with the side trimmer to cut the trimmings automatically into easily disposable lengths, regardless of the operating speed of the line.

To permit a continuous movement of strip through the acid tanks, a large looping pit is located between the entry section and the processing section. This looping pit provides storage for the strip so that the entry section of the line may be stopped without stopping the rest of the line. The entry section must be stopped for charging the line and joining the new coil to the end of the previous coil. Pinch rolls are strategically located to provide the necessary power for strip propulsion.

In order to obtain the wide speed range required for this line, adjustable voltage dc control is used. Separate generators are used for the entry, processing, and delivery sections. Each generator has its individual magnetic-amplifier type voltage regulator with current-limit control and *IR* drop compensation. The magnetic amplifiers are used to excite the generator shunt fields and thereby control the generator armature voltages. Speed synchronism of the line is obtained by having the reference windings of all the magnetic-amplifier voltage regulators excited from a common source. This common reference source is another magnetic amplifier, with its output varied by means of a line speed setting motor-operated rheostat. The pace of the line is set by pinch roll 2, which controls the speed of the strip through the acid tanks.

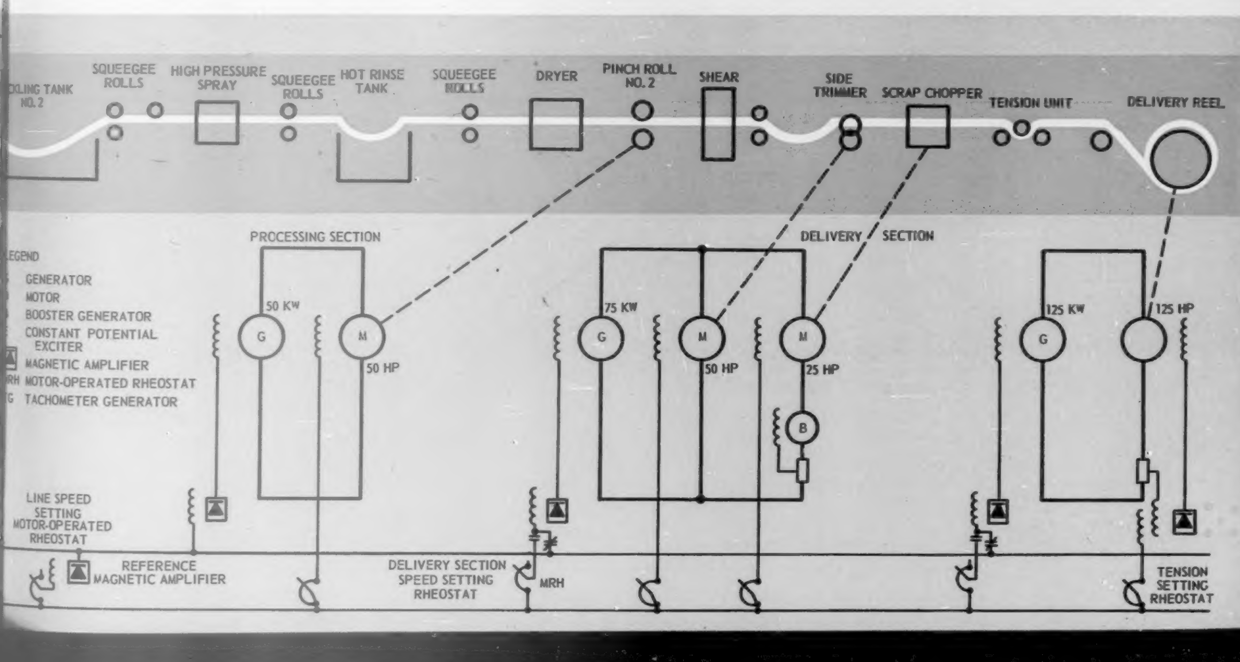
After a new coil has been put into the line and the entry section stopped to join the coil ends, it is necessary to overspeed the entry section in order to refill the looping pit. The same magnetic amplifier that accelerates the entry section motors under current-limit control also governs the overspeed. After the looping pit is full, the operator then brings the entry section back into synchronism with the processing section. The transition from overspeed to synchronous speed operation is done under current-limit decelerating control. Current-limit control results in minimum down time by providing maximum acceleration and deceleration of the line motors. The control of the delivery section is similar to that of the entry section. Because less time is required to shear the strip and remove a coil, the strip storage capacity and speed-up of the delivery section need not be as great as that for the entry section.

A magnetic-amplifier current regulator is used to control the current of the delivery reel motor. This regulator operates on the reel motor field and keeps the tension in the strip constant while the metal builds up on the reel. To keep all motors in speed synchronism over the wide operating speed range of the line, it is necessary to have booster generators in series with the armatures of pinch roll 1 and the scrap chopper. The booster generators are used primarily to compensate for *IR* drop in the motors.

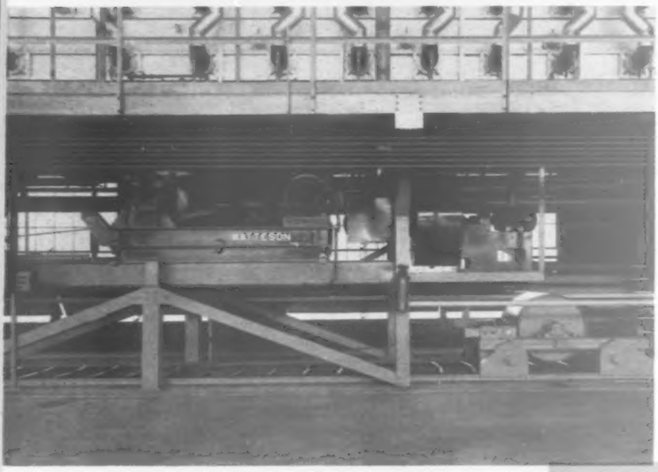
Annealing line controlled

The annealing line is one of the most important processing lines in the strip mill and is in some respects similar to the pickling line. The line consists of three sections: entry section, processing section, and delivery section. The entry and processing sections are shown in Figures 4 and 5. Figure 6 shows the line schematically.

The entry section consists primarily of equipment for uncoiling the material and joining the head end of an incoming coil to the tail end of the preceding strip. The payoff reel, the shear, and the welder which joins the coil ends are located here. The two pinch rolls in this section are ac motor driven and are used primarily to position the strip for the welding and shearing operations, and for initial threading of the line. As in the pickling line, some provisions must be made for storing the strip so that the movement of the strip through the furnace section is continuous, even though the entry section is stopped for coil



WELDING of new strip to previous strip at entry end of annealing line is accomplished without stopping strip in furnace. **(FIGURE 4)**



HORIZONTAL LOOP CARS driven by eddy-current clutch controlled winches store strip for uninterrupted heat processing. **(FIGURE 5)**

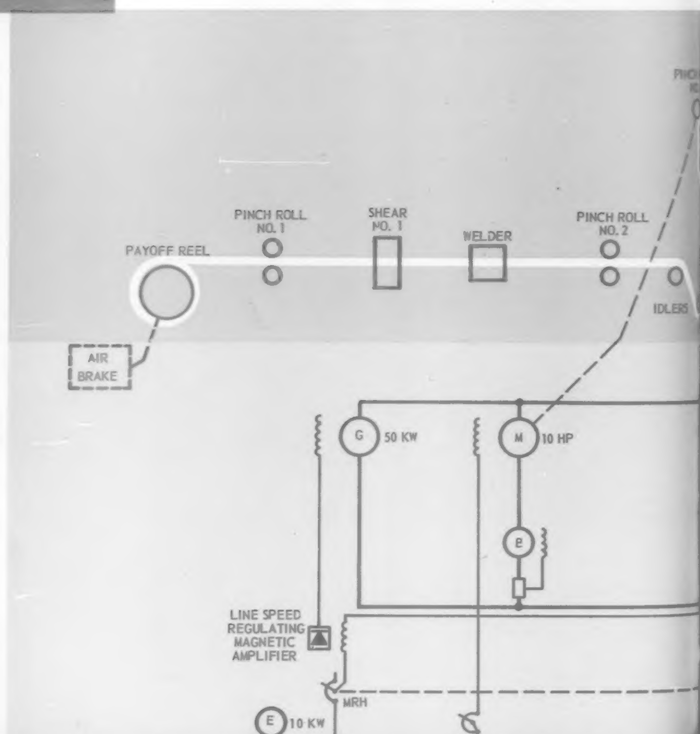
charging and welding of coil ends. Strip storage is accomplished by means of a loop car operating on tracks beneath the furnace. The strip is looped around a large idling roll mounted on the loop car. The loop car itself is pulled by means of a winch, which is driven by an ac motor through an eddy-current coupling. As soon as the entry end is stopped, the loop car moves in the pay-out direction. This action is accomplished automatically, since the pull exerted by the furnace entry pinch roll then exceeds the pull of the winch on the loop car. When the entry section is again started, the loop car moves automatically back into its maximum loop position.

The processing section consists of a long horizontal gas-fired furnace, which includes the preheating section, the controlled atmosphere heat-soaking section, and the cooling section. The strip is moved through the furnace by means of four motors mechanically connected to the drive rolls in the furnace. Pinch rolls and tension bridles are located at the entry and exit sections of the furnace.

The delivery section of the line consists of the shear and the tension reel. As in the entry section, provisions for strip storage must be made in order to keep strip movement through the furnace constant. Horizontal strip storage is obtained by means of a loop car similar to that provided for the entry section. The tension exerted on the strip by the loop car is also automatically controlled by an eddy-current clutch which governs the torque exerted by the winch.

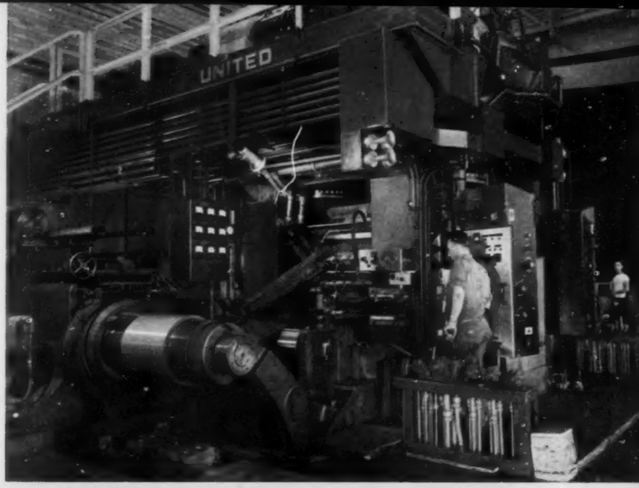
Line speed regulated

As in the pickling line, adjustable voltage control is used to vary the speed of the line. Two dc variable voltage loops are used, one for the furnace or processing section and the other for the delivery section. No dc generator is



VARIABLE VOLTAGE speed control, using the pinch roll at the exit end of the furnace as pace-setter, governs strip speed. **(FIGURE 6)**

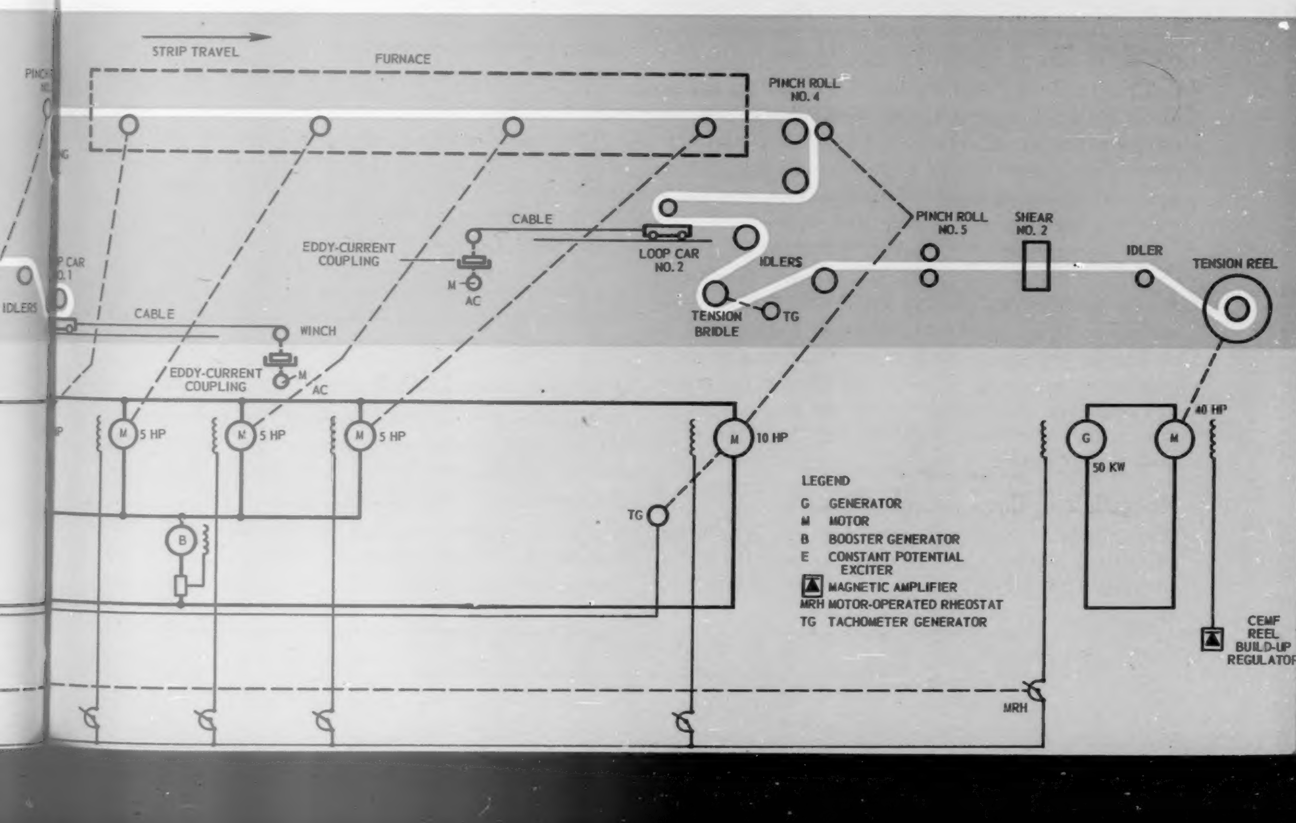
GENERATORS supply variable voltage for annealing line motors driving pinch rolls, furnace rolls, and tension reel. **(FIGURE 7)**

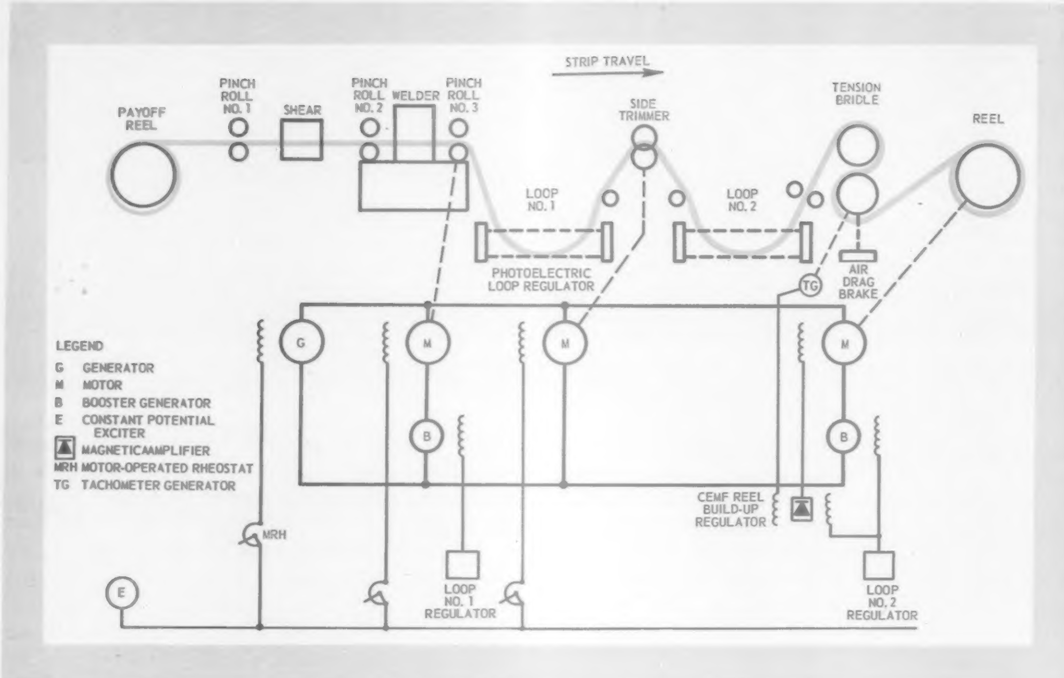


CRITICAL PERCENTAGE REDUCTION of transformer core steel requires high-speed, carefully coordinated control. **(FIGURE 8)**

used on the entry section, since back tension on the payoff reel is controlled pneumatically by means of an air brake. Ac motors are used in the entry section for threading and strip positioning. Because greater strip speed accuracy is required, a magnetic-amplifier type line speed regulator is used rather than a voltage regulator, with *IR* drop compensation as was provided for the pickling line. The pace setter for this line is the exit pinch roll of the furnace. A tachometer mounted on the exit pinch roll drive motor is used in a feedback circuit, which keeps strip speed constant by varying the voltage of the furnace section generator. To keep the speed of all the furnace section drive motors in synchronism with the rest of the line, a booster generator is connected in series with the furnace drive motors and with the entry pinch roll. The speed of the line is changed by means of the two-ring motor-operated rheostat shown in Figure 7. One ring is used to supply the reference voltage for the speed-regulating magnetic amplifier, the other ring is used to control the excitation of the delivery reel generator. By proper stepping of this rheostat ring, it is possible to have the speed of the delivery section match the speed of the furnace section.

When the delivery end is stopped for coil removal, strip accumulates in the delivery end looping car section. To remove this strip and return the loop car to its minimum stored strip position so that it is ready for the next delivery end shutdown, it is necessary for the delivery section to overspeed. As soon as the strip is threaded to the reel, the operator starts up the delivery section, which then accelerates to a preset top speed. The delivery section operates at this overspeed until the loop car returns to its minimum loop position. When this position is reached, a limit switch signals the control to bring the delivery section automatically into speed synchronism with the furnace section.





INSPECTION LINE is powered by single dc generator, and only the reel motor is controlled with a magnetic-amplifier unit. **(FIGURE 9)**

As the metal builds up on the reel, it is necessary for the reel to slow down automatically so that tension and strip speed remain constant. Speed is controlled by regulating the excitation of the reel motor field by means of a counter-emf reel build-up regulator. This magnetic-amplifier type regulator receives its strip speed intelligence from a tachometer generator driven by the tension bridle in the delivery section.

A pneumatic-type edge regulator is used on the reel to obtain a straight-edged coil. This device directs a jet of air against the edge of the strip and a sensing nozzle. The recovery air pressure, picked up by the sensing nozzle, is then converted by means of the regulator into a hydraulic force to adjust the position of the reel laterally.

A unique feature of the annealing line is the furnace drive creep circuit. This circuit automatically brings the furnace drive motors to creep speed whenever the line is stopped. Operation of the furnace rolls at creep speed is necessary to prevent roll warpage resulting from high temperatures in the furnace. Whenever the creep circuit is put into operation, the drive power for the furnace rolls is automatically transferred from the main generator to a small booster generator.

Magnetic amplifiers control mill

While the four-high reversing mill does not come under the category of processing lines, it is tied in with the silicon steel expansion programs. The mill, shown in Figure 8, is designed for operation at 2000 fpm and is powered by four 1500-hp dc motors. An unusual feature of this mill is the use of static-type regulators exclusively. These regulators are similar to and in some cases duplicate the magnetic-amplifier regulators used on the continuous pickling and annealing lines.

Inspection line controlled

The inspection line, shown in Figure 9, completes the processing at Midland.

The line is designed for a top speed of 600 fpm and receives adjustable voltage power from a single generator. Most of the line's equipment is conventional and therefore does not require elaboration. Photoelectric loop control is used on both sides of the side trimmer. A counter-emf type magnetic-amplifier regulator is used on the reel motor to compensate for reel build-up. An air brake and clutch are used on the tension bridle to provide back tension to the reel.

Package drive control used

Throughout these processes, many of the components in the magnetic-amplifier regulators are interchangeable. This feature minimizes the number of spare parts required for the magnetic-amplifier regulators.

The heat-flattening line, shown schematically in Figure 10, is the final processing line for some of the strip. Basically, the line consists of two sections — the

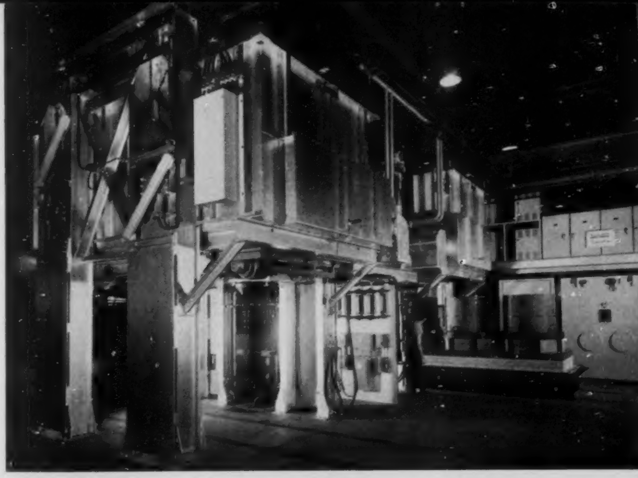
furnace section and the delivery section — each powered by a single generator. The entry, exit, and tension bridles are in the furnace section, while the delivery section consists of the coiling reel and a double-cut shear. A tension regulator is used on the exit bridle motor to control the strip catenary in the furnace. Strip tension is controlled by regulating the voltage of the booster in series with the exit bridle. A conventional counter-emf type of speed regulator is used for reel build-up compensation at the delivery end. All regulators used on this line are magnetic-amplifier type. To eliminate tension on the strip while it is being inspected, a shallow loop is automatically maintained just before the strip passes over the inspection table.

Since the heat-flattening line has no strip storage facilities, it is important that the heat in the furnace section be reduced whenever the line is stopped. This heat reduction is accomplished by controlling the gas valves in the feed lines to the furnace in relation to strip speed.

An outstanding feature of this line is the use of a packaged motor-generator set, regulators and control which are located close to the heat-flattening line drive motors. Important installation savings are realized by the compact package drive arrangement, since it eliminates all interconnecting wiring between generating equipment and control. Field checking is reduced because of the combined testing of rotating equipment with controls at the factory.

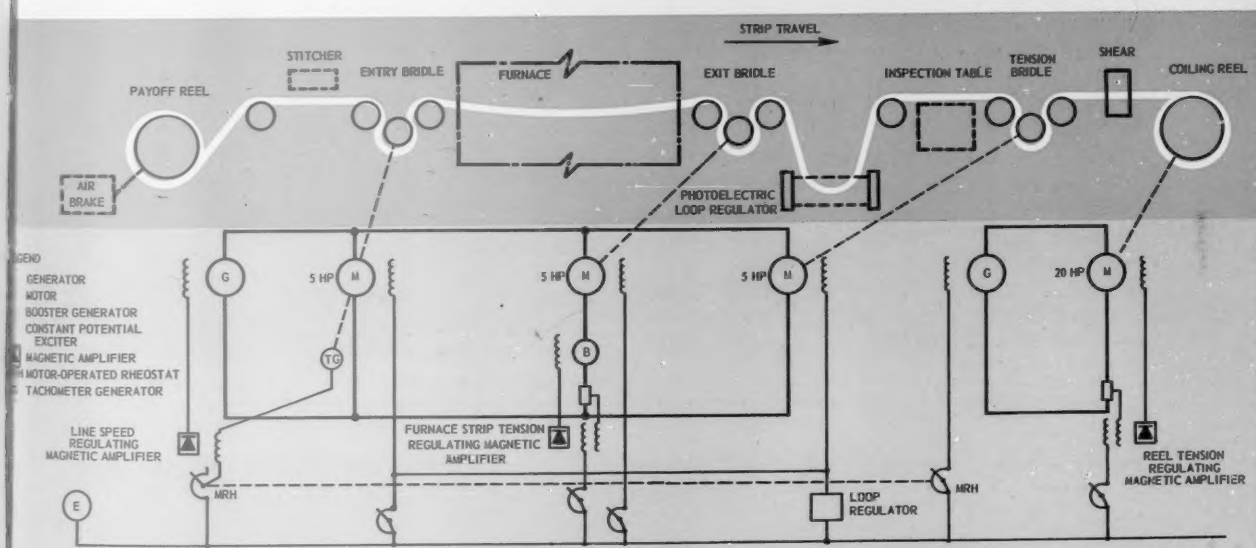
Figure 11 shows the transformer core steel coils being placed in high temperature annealing furnaces at Allis-Chalmers Pittsburgh Works. From these furnaces the coils may be sent into the heat-flattening line for finishing prior to being cut into shapes needed in the various cores. Figure 12 shows laminations being placed in the core of a transformer.

Careful coordination of all the processing, rolling and finishing of transformer core steel assures consistent core characteristics.

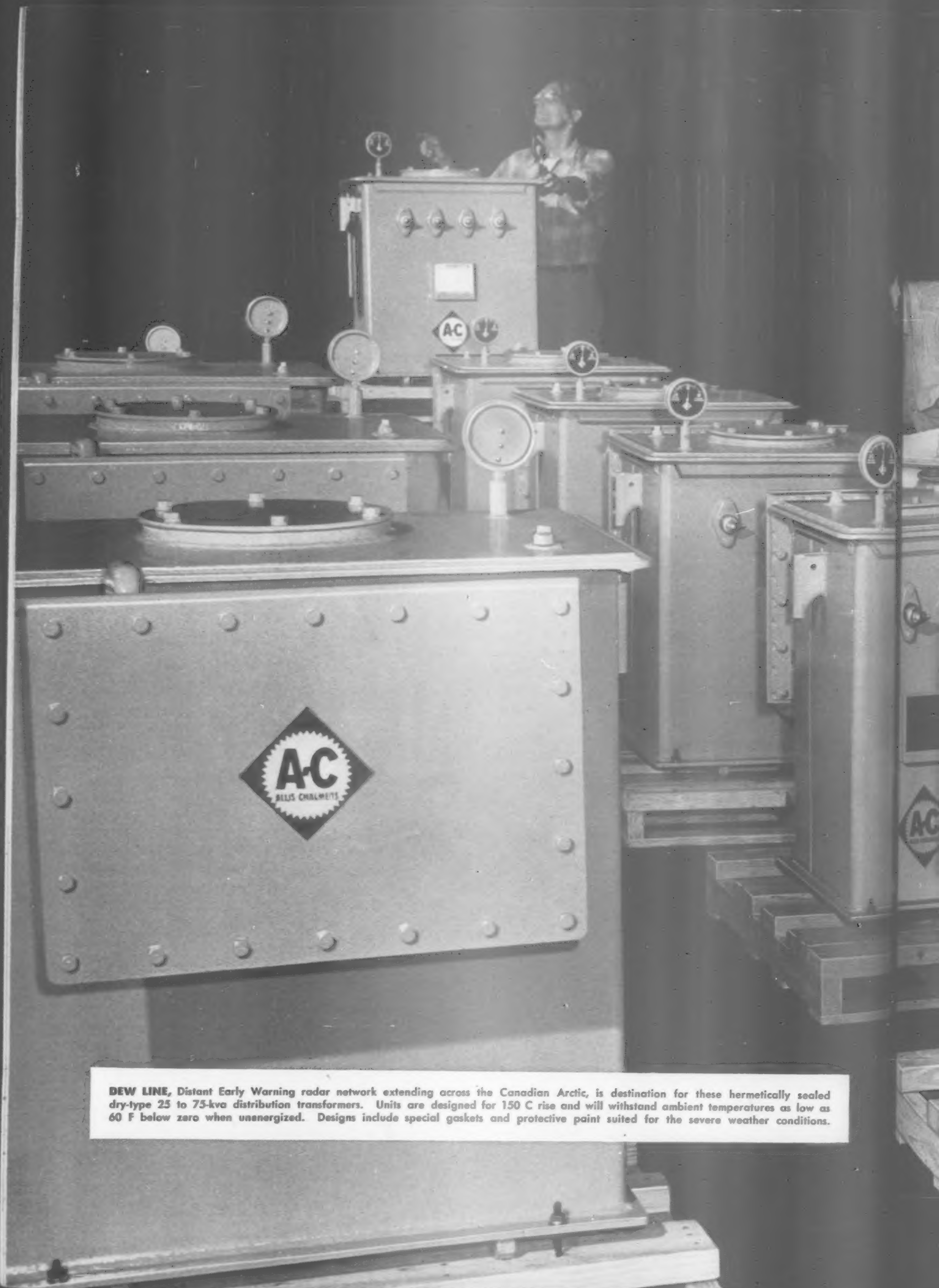


HIGH TEMPERATURE elevator-type annealing furnace provides final anneal for this special transformer core steel. **(FIGURE 11)**

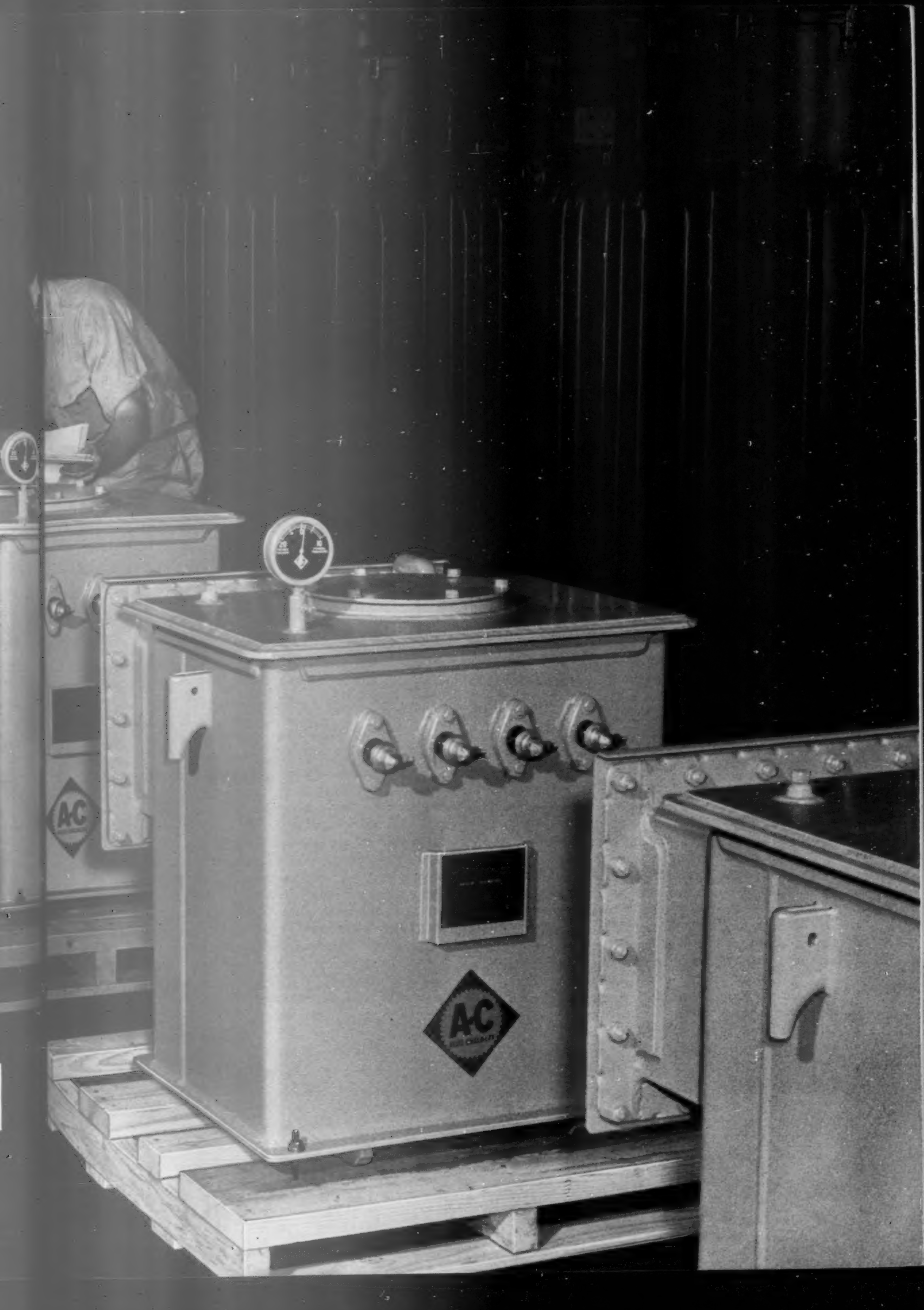
CONSISTENT CHARACTERISTICS of transformers depend on accurately controlled processing of the core steel. **(FIGURE 12)**



HEAT-FLATTENING LINE has magnetic amplifiers controlling line speed, furnace strip tension, and reel tension. **(FIGURE 10)**



DEW LINE, Distant Early Warning radar network extending across the Canadian Arctic, is destination for these hermetically sealed dry-type 25 to 75-kva distribution transformers. Units are designed for 150 C rise and will withstand ambient temperatures as low as 60 F below zero when unenergized. Designs include special gaskets and protective paint suited for the severe weather conditions.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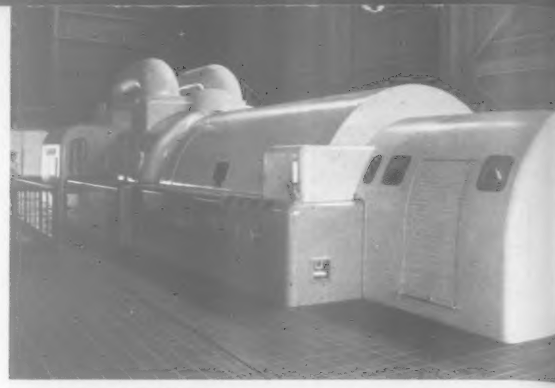
SPEAKING OF POWER FACTORS

by **R. A. GERG**
Control Department
Allis-Chalmers Mfg. Co.



COMPLETELY AUTOMATIC excitation control is trend for modern power stations. The 44,000-kw AIEE-ASME preferred standard unit at Georgia Power's Plant McManus is an example of this trend.

When discussing the control of reactive power in one of today's complex power systems or in a system component, the terms describing power-factor conditions may lead to confusion.

BECAUSE of lack of a common viewpoint, a group of engineers often finds difficulty in discussing the flow of reactive power in various parts of a system. When we talk about unity power factor, power flow in an ac system can be readily visualized. However, when other than unity power-factor conditions exist, there are various ways of describing the flow of reactive power — and terms such as the following are commonly used:

Leading current, lagging current, leading volts, lagging volts, reactive power in, reactive power out, leading vars, lagging vars, vars in, vars out, overexcited, underexcited, plus vars, minus vars.

Each of these terms will give the correct impression only when properly used and qualified.

Inadequately and improperly qualified power-factor terms can lead to confusion in discussing, for example, the flow of reactive power in a hydraulic pump-turbine. Under low system load conditions the synchronous machine becomes a synchronous motor, driving the turbine as a pump to store water in a reservoir.* Under peak system load conditions the same synchronous machine becomes a generator, driven by the stored water, and supplies power to the system. When the machine is operating as a generator and is overexcited, it is operating at a lagging power factor. When the unit is operating as a pump with approximately the same loading and excitation, the generator becomes a synchronous motor with a leading power factor. In both cases the flow of reactive power (vars) is out from the machine, while the power factor is lagging in one case and leading in the other. (A var — volt-ampere reactive — is a unit of excitation in somewhat the same sense as the ampere turn of a machine field.)

Thinking of power factor without carefully defining conditions may be confusing. However, if we think in terms of the unit itself and consider the machine overexcited in each case, the direction of reactive power flow becomes clear. (An overexcited machine supplies excitation to underexcited elements of a system, such as induction motors.)

If we consider all of the elements of a utility system simultaneously, the whole system is at unity power factor. By that is meant the sum of the vars into all of the underexcited elements of a circuit equals the vars out of the overexcited elements. To describe individual elements of the system as leading or lagging will make system power-factor conditions more difficult to visualize.

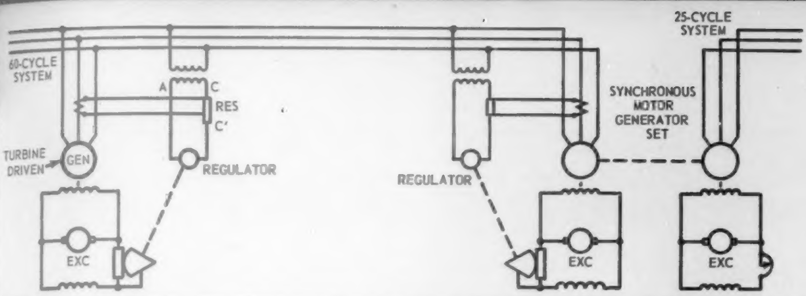
Terms qualified

There are many occasions when the operation of an individual system element is described, without qualification, as leading or lagging. In describing the operation of an induction generator, for example, some engineers may say it is operating at a lagging power factor. This statement can evolve by explaining its operation from induction motor theory. However, confusion can be avoided if it is made clear that the unit is underexcited before using the vector analysis applicable to an induction motor.

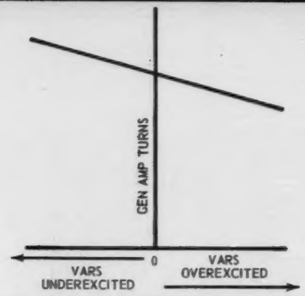
When analyzing the need for reactive compensation for the division of reactive power between two machines, a more direct solution can be obtained when the analysis is based upon one of the machines being underexcited or overexcited with relation to the other. If one machine is supplying more vars to the system than another an automatic regulator may be used to reduce the excitation of the one machine to balance it with the other. This applies to any mode of operation even if one machine is operating as a synchronous generator and the other as a synchronous motor, or if both are motors or generators. If we try to analyze this problem from the standpoint of leading or lagging power factor, the solution can become many times more difficult. A vector analysis to check the connections and the actual circuit requirements can be made more quickly if we think in terms of overexcited or underexcited operation of individual units.

The division of reactive power and the minimizing of circulating current between two synchronous machines are problems frequently encountered in the control of alternating current machines. On one system the control of circulating current between machines is complicated by having one of the two paralleled machines acting as a genera-

* "Generator-Motor Units for Reversible Pump-Turbines" by H. H. Roth, *Allis-Chalmers Electrical Review*, 4th Quarter, 1954.



VARS SUPPLIED by overexcited elements of a power system always equal the vars required by underexcited elements of the system. Vars supplied to the system by a synchronous machine are limited with reactive compensation in the machine's regulator circuit. **(FIGURE 1)**



REACTIVE POWER CONTROL is chief function of synchronous machine excitation regulating systems. **(FIGURE 2)**

tor one moment and as a synchronous motor the next, while the other unit is a generator only. The variable machine in this case is a part of a synchronous motor-generator set. One unit of the motor-generator set is a 60-cycle machine, the other a 25-cycle. The motor-generator set is used as a tie between the two systems, and when one system load increases relative to the other, power is transmitted through this machine set. Under normal conditions the set floats on the line.

On the 60-cycle side the fixed generation unit and the variable unit are equipped with voltage regulators. Since both units are but a small part of a large system, the regulators can control only reactive power and circulating current between the two units. These units have a negligible effect on system voltage. The two machines are tied to a solid bus without any significant impedance between them. Because of this solid tie, the regulators are equipped with reactance compensators which divide the reactive power between the two machines and minimize the flow of circulating current between them. This system and its regulators are shown in Figure 1.

The potential and current connections to the regulator controlling the output of the fixed generator can be established. However, if we keep the reversible unit's excitation fixed and let the unit operate overexcited, first as a generator and then as a motor, the unit will be at lagging power factor as a generator and leading power factor as a motor.

Direction determined

If we momentarily forget about power factors and think in terms of overexcited or underexcited operation, we can establish a common starting point from which to attack the problem.

When two or more units of a system are overexcited and therefore feeding excitation to the system, we frequently find one of the units furnishing more than its share. The excitation of one must be reduced while the other is increased so that the reactive power furnished by each machine is in balance. To obtain this balance a device sensitive only to reactive power is required. The device reduces the field excitation in one machine in proportion to the excess in excitation vars it is furnishing to the system. Similarly, the device increases the other machine's field excitation when it is supplying insufficient vars to the system. The same arrangement is used if the synchronous machine is a generator, motor, or condenser.

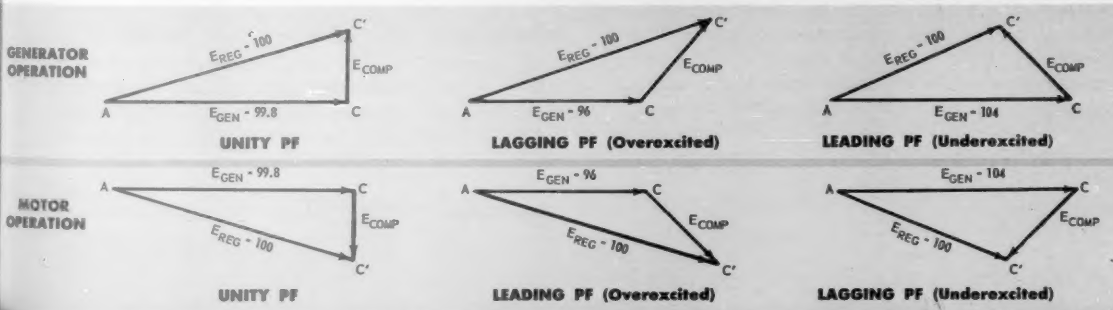
The reactive power control device is designed with the characteristics shown in Figure 2. While insensitive to real power, it reduces generator field excitation as the machine tends to increase flow of excitation to the system.

A voltage regulator is sensitive only to the voltage impressed on its terminals and functions to maintain this at a constant value. A resistor, shown in Figure 1, is located between the terminals of the potential transformer and the regulator terminals to establish a voltage gradient between them.

Figure 3 shows how the reactive compensator fools the voltage regulator by modifying the measure of generator voltage and causing the regulator to control the generator voltage in accordance with machine reactive loading.

When a generator changes to synchronous motor operation, its counter voltage is 180 degrees out of phase with its voltage as a generator. At the same time, the power component of current shifts 180 degrees, since it is in phase with the counter voltage of the motor. Power flows into the machine when operating as a motor rather than out as it does when operating as a generator. The operation of the reactive compensator having all potential and current connections the same is shown in Figure 4. The vector *A-C* is the same as in Figure 3, since the connections have not been changed. The unit senses the phase angle of the system voltage. This angle is the same when the machine operates as a generator. These vectors show that no change in control connections is required to convert the generator to a motor.

While we resort to vectors for actual solution of power-factor problems, a common basis for talking about power-factor conditions can be established simply by dividing the portion of the system being discussed into overexcited and underexcited elements. This method is found to eliminate confusion among engineers discussing system operating conditions.



American Hydro Power in the 20th Century

HOOVER DAM is symbolic of the larger, more powerful hydroelectric projects. (FIGURE 1)

PART II

by **EDWARD UEHLING**
Hydraulic Department
Allis-Chalmers Mfg. Co.

DURING THE 1920's great forward strides in the art of water power development were evident. Water power sites formerly regarded as marginal were now being developed, bringing power and prosperity to new areas.

An incident involving a development on the Peshtigo River in Wisconsin typifies the rapid progress made in hydro-power practice during the second decade of the 20th century. Here, in 1909, a firm of consulting engineers designed and started construction on a plant at Johnson's Falls. However, work was suspended and the project postponed by the utility until 1922, when the decision was made to proceed with the plant. "Due to the progress in turbine design, and the development of the vertical generator, the powerhouse covered only one-fourth the area that would have been required by the horizontal turbine setting available in 1909."[27]

Improved technology during this same period resulted in many of the multiple-runner Francis turbines installed during the early 1900's being replaced in the 1920's by single-runner, fixed-blade propeller-type turbines. For example, the 1909 vertical triplex unit of the Hanford (Calif.) Irrigation and Power project (see Part I, Figure 6) gave way to a single vertical propeller turbine. Operating at the same speed, the new unit delivered more power under 14-foot head than the three older Francis runners developed under 18-foot head. Not only was plant revenue greatly improved, but the four passage openings of the propeller runner were less likely to clog.

American adjustable-blade wheels

As large size and more efficient propeller runners came into use, it was recognized that better overall operating efficiency could be obtained if the tilt of the propeller blades could be changed to suit variations in head or seasonal flow. One method, used as early as 1923, was to seasonally unwater and adjust the blades at the hub, making the setting secure by bolts or dowels.

An earlier attempt to control flow by positioning turbine runner blades is indicated by the August 20, 1867, patent of O. W. Ludlow, of Dayton, Ohio. While neither a Francis nor propeller turbine, this odd arrangement of unknown application had for its objective, the patent states, . . . "the varying of the discharge of the water from the wheel by varying the capacity of the (runner) issues, and also by regulating the suction of the draught wheel, whereby the capacity of the wheel may be regulated to suit the amount of power required." In view of modern venting of hydraulic turbines, of incidental significance in this patent, see Figure 2, is the "ventilating pipe, *P*, which extends up above the surface of the water . . . a valve, *Q*, inserted in it, which is turned or operated by a governor or otherwise, so as to give more or less vent to the tube, *P*."

By 1926 a number of designs more convenient than seasonal unwatering had been worked out and patented. In these, mechanical adjustment in the hub could be made from above, at the turbine-generator coupling, with the unit at rest, see Figure 3. In some, geared operation of the propeller blades was accomplished by an internal adjusting shaft. The latter design was very successfully used in the first four large adjustable-blade propeller units installed at the Rock Island plant on the Columbia River in 1932. In other designs the adjustment was made by a camlever motion through an internal push-pull rod.

A third adjustable-propeller type used as early as 1930 was the "Motormatic," which consisted of a gear interlocking ratio, operated by an electric motor inside the shaft, for adjusting the runner blades while at rest or in motion. See Figure 5.

Automatically adjustable propeller blades

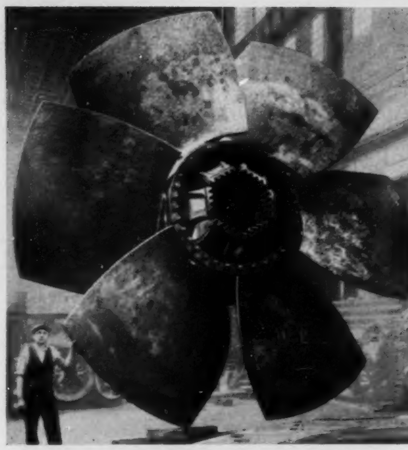
Based on studies in 1928, one turbine manufacturer developed a design known as the Terry turbine. The first unit of this kind, rated 7600 hp under 23-foot head at 90 rpm, was "placed in service in December 1935" on the Kenawha River near Charleston, West Virginia.[28]

In this design, "the vanes are pivoted with their centers of pressure. When water flows past the vanes, it sets up a moment, termed hydraulic moment, tending to open or increase their pitch. . . . Two forms of reacting devices are employed; the principal one admits scroll-case pressure to the top of the dashpot piston and draft-tube pressure to its under side. The auxiliary or adjustable reactive device comprises heavy duty, railway springs installed in the hollow turbine shaft and adjustable by a screw at the upper end of the generator shaft . . . action of the arrangement constituting the principal reactive device. . . ."[29]

Kaplan adjustable propeller runners prevail

All types of adjustable-propeller runners previously mentioned were installed, but only in very limited numbers. During the past 25 years a more versatile adjustable design has been used almost universally. It has a coordinated oil pressure piston control, or servomotor, operating inside an enlarged turbine shaft, see Figure 6. This type, "known in the hydro-power industry as the Kaplan turbine, in honor of its inventor, Dr. Viktor Kaplan, of Brunn, Czechoslovakia, was first introduced in Europe in the early 1920's and in the United States in 1928. Since then, approximately 274 units with a total output of 7,647,000 hp have been installed, or are under construction, in this country. Runner diameters vary from 30 to 292 inches, and maximum operating heads for the individual units range from 7 to 105 feet. . . .

"The main feature of the Kaplan turbine is the simultaneous adjustability of its runner blades and wicket gates which, when properly synchronized for varying conditions of load, results in a very flat efficiency curve, thereby improving part-load efficiency over other reaction-type turbines by a considerable amount. Being essentially an infinite number of propeller runners with different blade angles built into one unit, the Kaplan turbine maintains high efficiency over a wide range of load. . . . The trend today in Kaplan turbine installations is primarily toward higher heads into the region where Francis turbines heretofore have been the only practicable choice."[30]

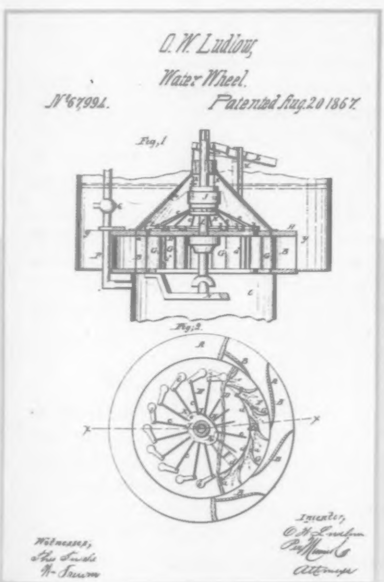


THE 21,000-HP RUNNERS for Rock Island, with blades adjusted by hand or air motor, were among the largest when built in 1932. **(FIG. 4)**

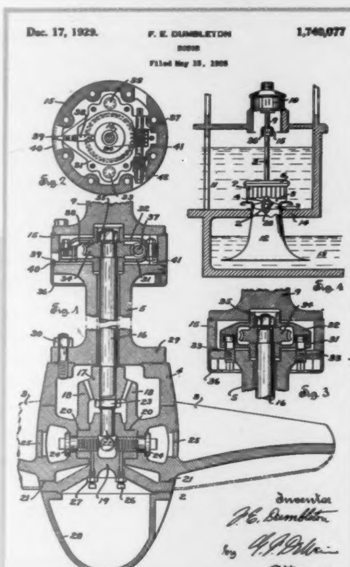
Next to the 212-inch Rock Island runners (see Figure 4) the largest capacity manually adjustable blade runner units were the six 12,000-hp (8800 hp best efficiency), 26-foot head, 85.7-rpm units installed in 1927 and 1928 at the Back River plant in Quebec. Three of these measured 192 inches.[31] See Figure 7.

The first Kaplan-type unit designed and built in the United States was for the Lake Walk plant near Del Rio, Texas, which was placed in operation in May 1929. Comparatively small in size, it was rated 1900 hp at 277 rpm under 33-foot head.[32]

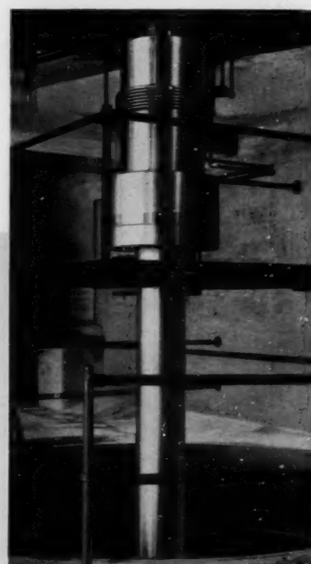
New records were continually being established by various manufacturers of Kaplan turbines. By 1932, at the Safe Harbor plant on the lower Susquehanna River, six 42,500-hp units for 55-foot head had been undertaken, then "the highest powered in the world, having runners 18 feet 4 inches in diameter."[33] Largest in physical size in this country today are the six Pickwick Landing plant concrete spiral-casing turbines on the Tennessee River. These deliver 55,000 hp at 81.8 rpm under a rated head of 43 feet. The runners, 24 feet 4 inches in diameter, are still



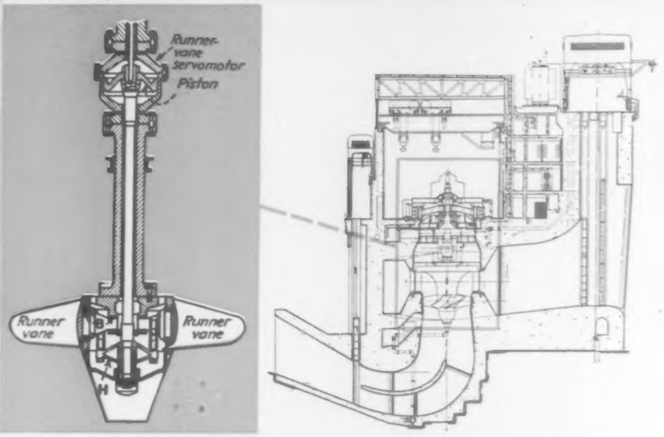
IN THE LUDLOW WHEEL, adjustment of buckets, G, controlled size of issues, d, between the buckets. **(FIGURE 2)**



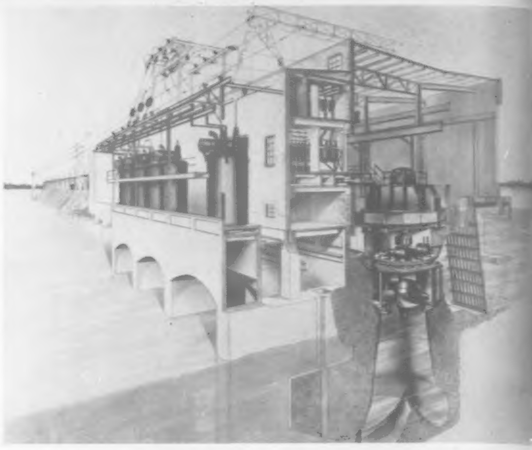
IN THE DUMBLETON patent, propeller runner blades were adjustable from the turbine shaft coupling. **(FIGURE 3)**



A 3000-HP, 20-FOOT HEAD propeller turbine at Sault Ste. Marie, Mich., had "Motormatic" adjustment. **(FIG. 5)**



STILL AMERICA'S LARGEST Kaplan turbines, the first Pickwick Landing units, shown in powerhouse and detail cross sections, were installed in 1938. **(FIG. 6)**



AN OUTSTANDING Canadian plant when installed in 1927 is the Back River plant in Quebec, which has manually adjustable-blade propeller turbines. **(FIGURE 7)**

(1955) the largest. The first two units, see Figure 6, were put in operation in 1938.[34] Quite significant when installed in 1942 were two 70-foot head, 120 rpm, 40,000-hp Kaplan turbines for the Santee Cooper plant, 35 miles north of Charleston, S. C. The plate-steel spiral casings for these turbines had 15½-foot inlet diameters. The units, shown in Figure 8, were furnished with automatic one-shot grease lubrication.

Kentucky Dam, located close to the mouth of the Tennessee River, near Gilbertsville, contains five 44,000-hp, 48-foot head, 78.3-rpm Kaplan turbines. These also are among the largest in physical size, having 21-foot 8-inch diameter runners. The first four went into operation in 1945.

The world's most powerful (1953) Kaplan propeller units, each rated 111,300 hp at 80-foot head, are installed at McNary Dam. These will soon be eclipsed by the 123,000-hp, 81-foot head Kaplan units for the Dalles Dam. Both dams are on the Columbia River in Washington. Huge water power developments like these are causing vast new industries to spring up in our formerly less populated western areas.

Believed to be the earliest Kaplan unit in the United States having a plate-steel spiral casing is one which has been in operation since 1932 at the Little Falls plant on the Passaic River in New Jersey. It is rated 900 hp at 360 rpm under 32-foot head, with a 49-inch runner driving a 750-kva generator, shown in Figure 9. One of the most recent and probably the largest turbine in physical size with riveted plate-steel spiral casing is the 195-inch Kaplan unit put in operation during 1955 at the Shepaug plant on the Housatonic River in Connecticut. It is rated 57,000 hp at 138½ rpm under 96-foot head.[35] The casing inlet of this unit is 25 feet in diameter.

Improvements in the art are many

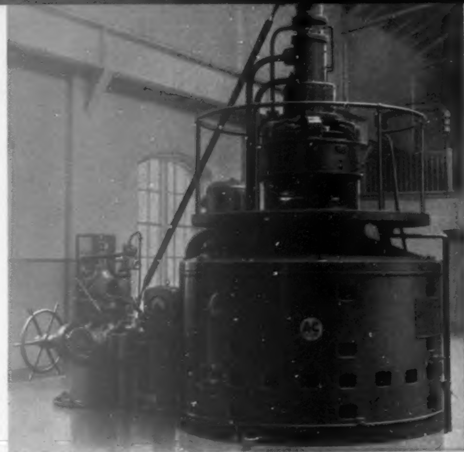
As demands for economical electric power increased, hydraulic turbines of larger and larger physical size were continually being designed. New manufacturing methods had to be devised. For example, as greater capacity low-head hydraulic turbines were built, cast-iron wicket gates became larger and heavier and more difficult to make. This brought about the Franz Schmidt patent of November 27, 1917, by which wicket gates could be fabricated of lighter riveted plate steel, as shown in Figure 10. New approaches to old problems made other improvements inevitable.

Many turbines, even the larger ones at Niagara Falls where the water was very clear, had adjustable lignum vitae water-lubricated type main bearings. Oil-lubricated babbitted-type main bearings, however, gained preference among engineers, not because the lignum type gave trouble, but because babbitted bearings were simpler and were believed to be more reliable. Many kinds of oil-lubricated bearings have been designed and successfully used. For example, the large propeller units at Green Island (see Part I, Figure 25) were of a self-lubricating type in which an endless flexible spring, driven by the shaft itself, moved through the oil reservoir and brought up a continuous supply of oil. The Davis Bridge turbines (see Part I, Figure 21) had viscosity-type pumps, whereby a shoe scooped up oil as the shaft revolved, and carried it to the top of the bearing. In more recent years, babbitted-type bearings having two motor-driven oil pumps — one driven by an ac motor for regular use, the other by a dc motor for emergency standby use — have been commonly used for large installations.

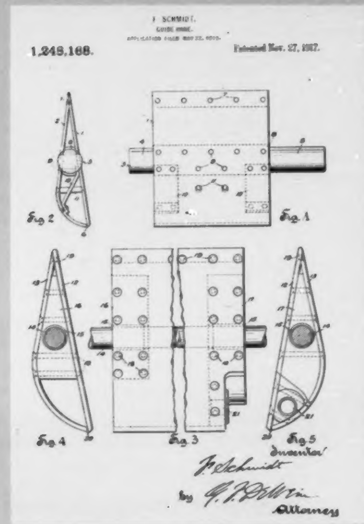
Another recent type of oil-lubricated bearing is shown in Figure 11. Successfully used on a number of installations in the last ten years, this bearing is self-lubricating and eliminates all mechanical means for circulating oil. "The bearing runs in an oil bath covering about one-third its length. The babbitt in the bearing has spiral gooves so that rotation of the shaft produces a pumping action. Oil is forced from the oil reservoir to the top, where it floods the entire bearing. The main feature . . . which makes its use possible . . . is a leakproof oil reservoir (which) requires the shaft to be hollowed out . . . to permit installation of an oil reservoir which does not have to depend upon a stuffing box around the shaft."[36]

As heads became higher, many improvements were devised for reducing leakage and wear. Water and grease-lubricated carbon seal rings below the main bearing, instead of a stuffing box, have been used on a number of more recent hydraulic turbine installations. "Wear along the discharge ends of the wicket gates and along the seal point also present a problem in medium and high-head installations. The insertion of stainless steel strips at these points tends to reduce this wear considerably. . . . Inlaid

KAPLAN runner, suspended in crane, ready for installation at Santee Cooper plant. **(FIG. 8)**



EARLY KAPLAN unit at Little Falls with 750-kva generator, oil distributor to servomotor, and governor relay connection. **(FIGURE 9)**



THE SCHMIDT PATENT covered plate-steel fabrication of large wicket gates for low-head turbines. **(FIG. 10)**

rubber strips have also been used on the gate seals and in the head covers and bottom plates to reduce leakage."[36]

Francis record at Isle Maligne development

"When completed, the hydroelectric development which the Quebec Development Co., Ltd., is now (1923-24) undertaking will be one of the largest in the world. This station is located on the Saguenay River about 30 miles upstream of Chicoutini, Quebec, and approximately 9 miles below Lake St. John. . . . When completed, this plant will contain twelve 45,000-hp (actually 50,000 hp obtained) hydroelectric units operating under 110-foot head at 112½ rpm. The major part of the twelve complete turbines were ordered under one contract."[37] This contract covered eight complete units, stay rings and casings for four more. This constituted the largest single contract for hydraulic turbine equipment ever consummated up to that time.

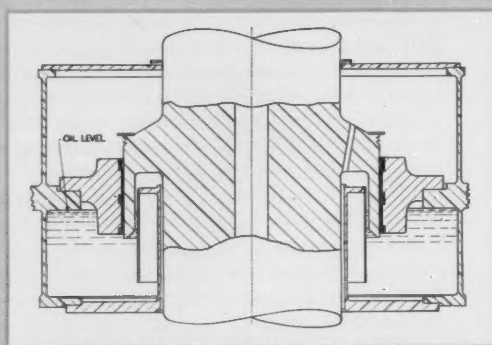
The spiral casings at Isle Maligne (see Figure 12) have 20-foot inlet diameters and plates varying from ⅞ to ½ inch in thickness, designed for riveting in the field. The one-piece cast-iron Francis runners have 15-foot maximum diameters (11 feet at the inlet) and are 8 feet high. Of special interest are the pitting plates (see Figure 13) which were introduced at this plant. Many different materials were tried, and stainless steel, for the first time, was found to be most effective in resisting pitting. Concrete *Hydraucone* draft tubes were used.

Mitchell Dam increased prosperity

Of special interest when they were originally installed about 1923 at Mitchell Dam on the Coosa River in Alabama, were three cast-iron runner, 70-foot head Francis units, each rated 24,000 hp at 100 rpm.[38] "Each of these units is installed in a structure located on the upstream side of the dam (see Figure 14) . . . generator and electrical equipment are located above the elevation of high water. The Thurlow backwater suppressor, installed for the first time, utilizes flood water to increase the head on the turbines . . . thoroughly tried out . . . exceeded expectations. . . .

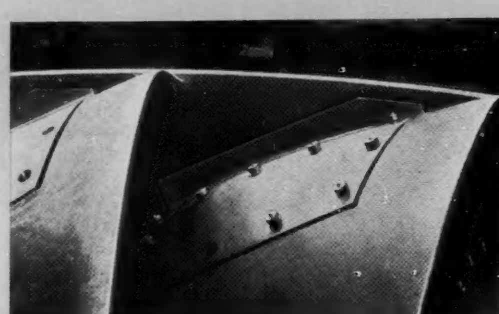
"Another feature is the outdoor gantry crane and the sliding roof of the powerhouse covering the generators. Two of the units are equipped with the *Hydraucone* and one with a flattened elbow draft tube. . . ."[39]

As in the case of propeller units, new Francis turbine records were continually being made. The Queenston-Chippawa and Isle Maligne plants in Canada had hardly been



SHAFT ROTATION PRODUCES the pumping action in a recent self-lubricated oil bearing. **(FIGURE 11)**

SPIRAL CASINGS at Isle Maligne, with 20-foot inlet diameters, were designed for field riveting. **(FIG. 12)**



PITTING PLATES were provided in the Isle Maligne runner buckets. **(FIG. 13)**

installed when greater records were being established by the three much larger size and capacity units at Niagara on the American side.[40] These were each rated 70,000 hp at 107 rpm under 213-foot head and actually developed about 85,000 hp. A best efficiency of 93.8 percent was obtained on the first unit at the time of installation. It was estimated that the operation of one unit alone would "release for other duties approximately 1500 men daily, who heretofore had been engaged in mining, hoisting, loading, hauling, switching, and firing coal under boilers in order to develop this same amount of energy."[39] Two of the turbines had cast-steel spiral casings of bolted together sections and spreading draft tubes. The third had a circular-section plate-steel type riveted casing, see Figure 15, and a *Hydraucone* draft tube.

Niagara casing presented riveting problems

"The greatest problem met in the design of the spiral casing for the 70,000-hp unit at Niagara Falls was the driving of the 1⅜-inch rivets, 6¾ inches long, through the flange of the speed ring and through the double thickness of plate; and also the driving of the 1⅜-inch rivets at the lap joints of the larger section of the casing where the plates are 1¼ inches thick. To drive these rivets a bullriveter was developed, and was constructed by the Hanna Engineering Works (Chicago). This machine is capable of exerting 150 tons with 100 lb air pressure and has a reach of 108 inches. . . . Figure (16) shows this riveter in action. On actual test it drove sixty 1¼-inch rivets per hour."[41]

At the upper end of the penstocks, instead of the customary type of square head gates, three record-size 23-foot 6-inch diameter, 50-foot head butterfly valves were used to shut off the water.

Conowingo 1928 world's record for size

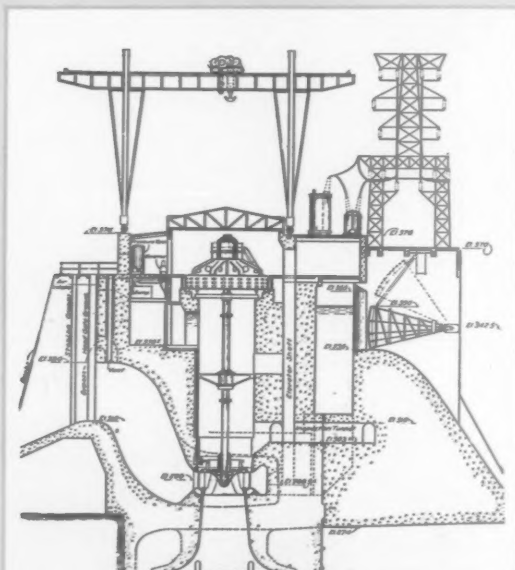
Seven riveted plate-steel spiral-casing Francis units were installed at the Conowingo plant on the lower Susquehanna River in Maryland. "They are all 54,000-hp machines at 89-foot net head and 81.8 rpm . . . two firms cooperated in design to an extent which made it possible for the runners to be interchangeable, so that only one spare has to be kept for all seven machines. . . . These machines, and the generators they work, constituted the largest units of their kind attempted at the time."[42] Three units had Moody spreading draft tubes, four had *Hydraucone* draft tubes.

"Plate-steel scroll cases were chosen on account of their greater economy when compared to concrete, which would require heavy reinforcing in the substructure and much more elaborate and expensive form work. . . . Butterfly valves, 27 feet in diameter, of vertical shaft, circular type, were selected as being the most practicable to suit the conditions . . . each valve sealed after closing by admitting water pressure to a rubber tube, 3 inches in diameter, set in the inside face of the valve housing opposite the periphery of the valve wicket. . . ."[43] These valves, see Figure 17, are still (1955) the largest ever built. Each cast-steel runner was 17 feet 9 inches, made in three sections and machined for assembly in the field.

Age of mammoth dams arrives

The 1930's saw the beginning of construction on a long series of gigantic dams and powerhouses which is still going on. These developments have been carried on by large government agencies,[35] such as the U.S. Bureau of Reclamation, U.S. Engineers, Tennessee Valley Authority, Canadian Hydro Commissions, and again more recently by industry and private utilities.

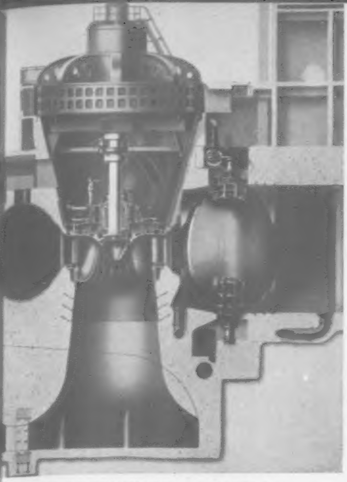
One of the earlier and better known of these huge developments is the Boulder Canyon project, consisting of Hoover Dam on the Colorado River, in Arizona and Nevada, see Figure 1. Considerations led to selection of



THE SEMI-OUTDOOR powerhouse and concrete spiral casing at Mitchell Dam attracted wide attention about 1923. (FIG. 14)

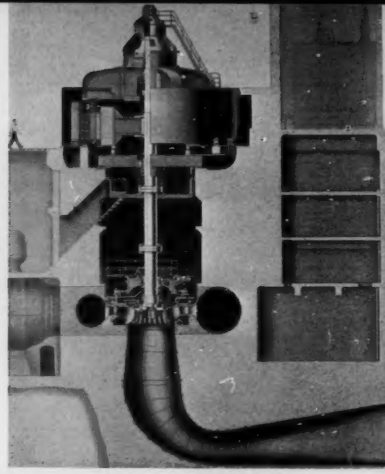
HUGE RIVETED casing at Niagara further demonstrated advantages of plate-steel construction. (FIGURE 15)

MASSIVE bull riveter at Niagara drove sixty 1¼-inch rivets per hour on actual test. (FIG. 16)



AT CONOWINGO the 54,000-hp turbines had 27-foot diameter butterfly valves, largest ever built. **(FIG. 17)**

AT FORT RANDALL eight 57,500-hp, 112-foot head runners are among the largest ever cast in one piece. **(FIG. 18)**



AT HOOVER DAM welded plate-steel casings were used for the two most recent 115,000-hp units. **(FIGURE 19)**

15 main units, each of 115,000 hp at 180 rpm under 480-foot head. At least nine of these, if they were not limited by their generator capacities, could develop 158,000 hp each at wide open gates under the maximum head of 590 feet. The first four were installed in 1936. Most of the units have cast-steel casings in convenient bolted sections, but the last two installed in 1950 are of welded plate-steel construction. The Hoover Dam project ranks second in capacity only to Grand Coulee on the Columbia River in Washington, where 165,000-hp units under 300-foot head were installed initially in 1941.[44]

Power from mighty dams like these helped bridge the power shortage of World War II and conserved untold quantities of fuel.

First all-welded spiral casings

At Shipshaw, the aluminum industry, with its tremendous demands for electric power ... 10 kwhr per pound of aluminum ... again demonstrated its ability to cut production costs by further utilizing our vast, ever-flowing water-power resources. Completed in 1943 and consisting of 12 units capable of averaging 100,000 hp each under 208-foot head at 128.5 rpm, the Shipshaw plant of the Aluminum Company of Canada, Ltd., is one of the largest prime mover plants in the world (steam or hydraulic) under one roof.[45] (Hoover has two separate powerhouses.) Turbines for this plant, located at the head of navigation on the Saguenay River, north of Quebec, have plate-steel spiral casings of welded design. Riveting was completely replaced for the first time on any major project. The casings, including the connection of the plates to the cast-steel flanges of the stay ring, were welded together in the field on installation. The inlet diameter of the spiral casings is 16 feet and their greatest overall width is nearly 50 feet. The maximum thickness of the welded joints is 1½ inches.

The Shasta plant of the Central Valley project on the Sacramento River in California consists of five plate-steel welded spiral-casing Francis turbines, the last one being put in operation in 1949. While rated 103,000 hp each under 330-foot head at 138.5 rpm, they are required to operate under extreme variations in net head, from 475 feet to 238 feet, because of storage and drawdown. At maximum head, each turbine could produce 187,000 hp if not limited by the 75,000-kw generator capacity. The spiral casings were the first of welded plate-steel construction to be built in the United States. Restrictions imposed by maximum allowable shipping space required that the spiral casings be built in seven sections. The Bureau of Reclamation's engineers specified riveted field joints. After welding and riveting in the field, the casings were successfully pressure tested to 310 psi static pressure — equivalent to 50 percent above 475 feet maximum expected head. A best efficiency of 92.3 percent was obtained.[46]

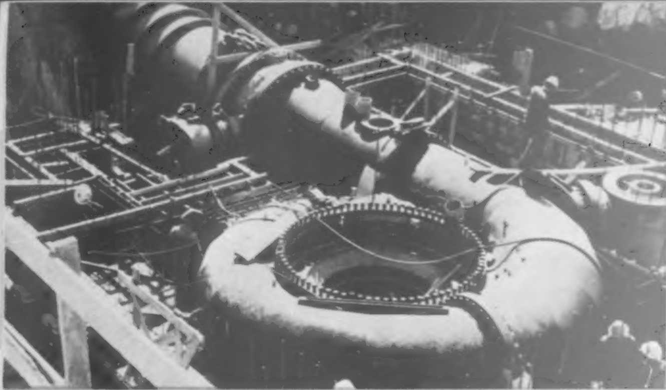
In recent years most large Francis runner turbines for medium or higher heads have been built with plate-steel spiral casings. Notable among these are huge units[35] like those furnished to TVA for Fontana Dam; to the U.S. Engineers for plants at Hungry Horse, Bull Shoals, and Fort Randall (see Figure 18); and to the Bureau of Reclamation for the last two units at Hoover. (See Figure 19.)

Welded scroll cases applied to high heads

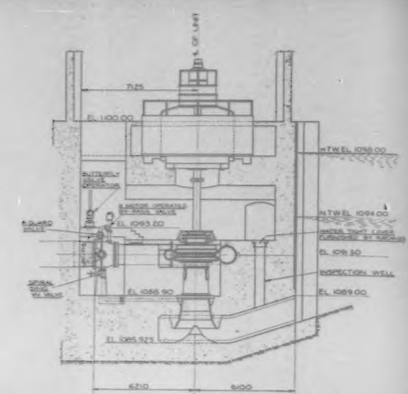
Recently completed (1955) are the welded plate-steel scroll case units for the Lemolo plants No. 1 and No. 2 on the North Umpqua River, Oregon.[35] Both of approximately the same physical size, the former is rated 40,000 hp at 400 rpm under 710-foot net head; the latter, 46,000 hp at 400 rpm under 705-foot net head. They represent the highest head so far attempted in plate-steel construction. (See Figure 20.) The scroll cases were constructed in halves of shop-welded steel, with bolted flange joints. Shop hydrostatic pressure tests were conducted at a pressure of 150 percent maximum operating pressure.

Francis turbines most extensively used

The Keokuk (1913) runners under 32-foot head, see Part I, Figure 8, seem to have been the largest of the earlier days. Among the largest, more recent single-piece runners are the eight now installed at Fort Randall on the Missouri River in South Dakota, see Figure 18. Said to be the largest one-piece Francis runners, also on the Missouri, are those installed recently at Garrison Dam, rated 88,000 hp at 90 rpm under 150-foot head.[35] Now under design and construction for Noxon Rapids on Clark Fork in northwest Montana (for 1958-1959 installation) are four 137,000-hp, 152-foot head, 90-rpm units with three-section runners having discharge diameters of nearly 19 feet.



THE 710-FOOT HEAD at Lemolo No. 1 is the highest yet attempted for plate-steel scroll cases. (FIG. 20)



FOR THE 808-foot head at Mexico's Santa Barbara plant, cast-steel casings were used. **(FIGURE 21)**

High-head Francis units require better material

Some of the earlier, progressively higher head Francis turbines were mentioned in Part I. However, in America, where the Pelton (impulse-type) turbine was developed and successfully used even prior to 1900[2] for heads up to 2100 feet, the desire to use Francis-type turbines for high heads, except in large ratings, has not been pronounced. Nevertheless, a few very high head plants, equipped with Francis turbines, furnished by various American water wheel builders, have been constructed. All have been vertical units with cast-steel spiral casings, some of which were made in several bolted sections.

By 1921 a 25,000-hp, 600-rpm unit for 800-foot head was built and installed at Kern River plant No. 3 in California.[47] Two years later, a 35,000-hp unit at 514 rpm under 860-foot head was built for the Oak Grove plant in Oregon.[48]

The Nantahala plant, "situated on the Nantahala River in southwest North Carolina near Franklin, was completed in July 1942 and has been in successful operation ever since. . . . The 60,000-hp (Francis) hydraulic turbine operates under 925-foot net head at 450 rpm. . . . Considerable stainless steel was used in the original installation and its use has been greatly extended. . . . This is believed to be the highest head reaction-type turbine installed in the United States and to be the highest-powered extremely high head reaction turbine in the world. . . ."[49] The bearing above the generator rotor is a Kingsbury spherical thrust bearing, capable of supporting radial as well as vertical loads. Francis-type turbines for a still higher record head were put into operation in 1953 at the Flatiron project on the Colorado-Big Thompson near Denver. These two units are rated 48,000 hp each at 574 rpm under a net head of 1045 feet.[35]

Mexico also has record Francis units

When the Ixtapantongo plant of the Comision Federal was put into operation in July 1944, a new record for high-head American vertical Francis units was established. This unit was rated 39,000 hp at 600 rpm under a net head of 1028 feet. To eliminate any heavy upward hydraulic thrust on the bottom of the wicket gate stems (see Davis Bridge, Part I, page 24), the lower gate stems of the Ixtapantongo unit extended through stuffing boxes in the lower cover ring, making them accessible from a pit surrounding the draft-tube top.[49]

The Santa Barbara plant, located near Taluca, 50 miles southwest of Mexico City, has three 500-rpm vertical Francis runner turbines, rated 33,000 hp (delivering 36,000) under a net head of 808 feet. See Figure 21. Each unit is designed for remote control from the nearby Ixtapantongo plant. Of these three units, the first two, having cast-steel runners and wicket gates, were installed in 1949. In the third, these parts plus facing plates and wearing rings were made of stainless steel.

The possibility of high speeds has given rise to the very high head Francis turbine. Some much larger capacity Francis units for still higher heads may well be expected. However, their wear and tear, lower settings, and problems brought about by long high pressure pipe lines can easily offset their advantages. Considerable attention is now being given to large capacity vertical shaft multi-jet impulse-type turbines for very high heads. A 428.6-rpm, six-jet vertical unit, rated 39,000 hp under a net head of 1233 feet (376 meters), was put into operation (1955) at the San Bartolo plant in Mexico.[50]

Hydro power grows in stature

In modern use, water power "is no longer thought of as competitive with, but rather as complementary to steam power. It is found that a combination of water and steam power has important advantages in that it can be quickly put on the line and can give an immediate response to increased load.[51]

"When nuclear power plants take their part in power generation on a large scale . . . as far as can be ascertained from the most reliable sources, they will (like the steam plant) have to run at as near 100 percent load factor as possible. . . . Nuclear power-station developments include the necessity to supply cooling water in almost the same order of magnitude as that required for thermal (steam) stations. . . . It becomes obvious that the linking together of hydro power and nuclear power will be much easier than the linking together of steam power and nuclear power. . . . Cooling water and the safety problem might be solved by installing the nuclear power stations at the same sites as those where hydro power is developed. . . ."[52]

Water power eminently worth while

Even the present 52 million developed horsepower existent in the U.S. and Canada cannot lightly be brushed aside from the standpoint of our economy. And still an esti-

mated 88 million more potential kilowatts of hydro power, in the U.S. alone, are reported waiting to be harnessed. About 54 percent of this potential is in the river basins west of the Continental Divide.[53] In recent years greater efforts have been made to use the full potential of entire rivers, including supplementary storage reservoirs of adjacent areas. The Raquette River in northern New York, known as the *Work Horse River*,[54] is controlled by a utility company. Unique is the Wisconsin River, known as the *hardest working river*,[55] where an associated group of industries and utilities along its course work together. Well known is the Tennessee River, where all sites are controlled by a Federal Authority.

In connection with rivers having adequate reservoirs, one of the most promising new types of hydroelectric unit is the reversible pump-turbine.[56] These units, operating as motor-driven pumps, utilize cheap off-peak power to pump large quantities of water from a lower reservoir to an upper reservoir. When peak power is in demand, the same unit takes water from the upper reservoir and operates in reverse as a turbine-driven generator to produce valuable peak-load power. Already (1955) there are two major installations in this country, one at Flatiron near Denver and the largest at TVA's Hiwassee Dam.[35]

Even an average size water power project of today would have staggered the imagination of the most optimistic proponents of water power as recently as the early decades of this 20th century. Nevertheless, each year we continue to find major new water power developments[35] of which our continent can be proud, not for size alone, but from the standpoint of national conservation of our natural resources.

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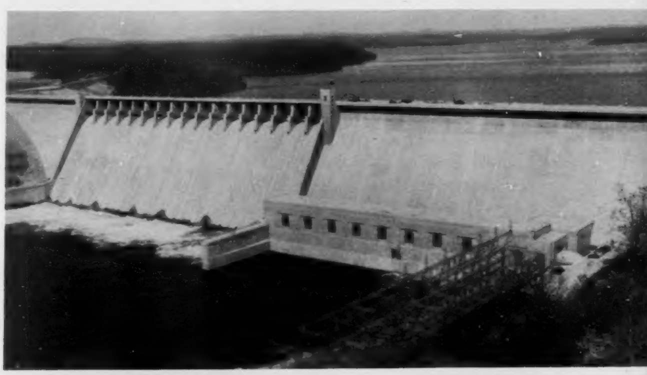
MODERN EQUIPMENT facilitated transportation of this large Hiwassee pump-turbine section from railroad to installation site. See Fig. 18, Part I. **(FIGURE 22)**



BULL SHOALS DAM on the White River in Arkansas has four 62,000-hp turbines in its powerhouse to combine power generation with flood control. *(Army Engineers Photo)* **(FIGURE 23)**

ALUMINUM vs. COPPER

For Step Regulators

by C. W. NIELSEN
Allis-Chalmers
Transformer Department

HELIUM-SHIELDED arc welding of aluminum to aluminum makes excellent connection. **(FIG. 1)**

Shortages of copper and rising copper prices are forcing electrical manufacturers to look to aluminum.

CHANGING over step-type regulators from copper to aluminum involves many design and production problems. Aluminum-wound units recently completed and tested provide answers to questions most likely to come up if aluminum is adopted for regular production of regulators.

To make the conversion to aluminum coils in step regulators, the following conditions should hold true:

1. Aluminum-wound units must be equal to or better, both electrically and mechanically, than the equivalent copper-wound units.
2. The overall size of the aluminum-wound units should approximate copper-wound units to permit their use as replacements.
3. The cost of manufacturing aluminum-wound units must be equal to or less than that of the copper-wound units.
4. Aluminum must be available in quantities sufficient to assure continuous production for the foreseeable future.

There are common construction methods which tend to simplify the changeover. All connections that are normally brazed in the standard copper-wound units are either brazed or welded in aluminum units; and since both types are oil filled, connections between aluminum and copper are made under oil, thereby eliminating galvanic corrosion problems. Tap leads on the series winding are bolted to the mechanism contact studs in both types. The aluminum and copper are joined between the coil and the mechanism studs to permit the use of copper-to-copper bolted joints. This arrangement permits the use of copper bushing leads for connection to the brass or copper terminals.

High frequency helium-shielded arc welding provides an excellent electrical as well as mechanical connection between aluminum parts. Helium prevents oxide from forming while the metal is melted and joined. Argon may also be used for this purpose. This welding method is shown in Figure 1.

Brazing or welding aluminum to copper, however, is more difficult. Special techniques are required in the application of heat to both metals. The flux which is used is quite corrosive and necessitates scrubbing the connection with a stiff brush and flooding it with water to avoid oil contamination in the finished unit.

Welded joints between aluminum and copper tend to be brittle. Alloys formed when the metals are in a molten state include those having more than 10 percent dilution in each other and are in all probability brittle. A 35-65 alloy, for example, is as brittle as glass. Since it is impossible at present to avoid such alloy combinations, other methods were investigated. A cold-pressure type butt connection was made on a machine which cuts parallel faces on the surfaces to be joined and forces them together hydraulically, creating a molecular bond which is stronger than the aluminum and is not brittle.

Aluminum-wound units built

Several feeder voltage regulators were built using standard construction, including cores, end frames, tanks, bushings and insulation, but having special coils in which aluminum magnet wire was substituted for the copper. Standard load tap changers with Elkonite-tipped contacts and other cop-

per or copper alloy current-carrying parts were used in these units.

Winding the main coil with aluminum presented no problems until the aluminum taps were added. Normal procedure with a copper winding is to maintain tension while making the brazed tap connection; however, when this procedure was followed with aluminum wire, the aluminum connections separated. Thereafter, tension was released before the wires were heliarc welded.

The winding procedure worked well with single-strand conductors and tap leads. However, the connections required greater care in higher current ratings, where the coil conductors consisted of 18 strands of aluminum and the tap leads 10 strands. With the heliarc process a union of aluminum occurs only where the actual weld is made. Since there is no flow as in a copper-brazed joint, strands of the tap leads were welded individually to the conductor strands. This method necessitated separating the tap lead strands slightly to permit individual welding, as shown in Figure 2.

Some difficulty was encountered in winding the auxiliary coils. These potential and current transformer windings are made with small-size round magnet wire with normal tension. Since the tensile strength of aluminum wire is much lower than that of copper, with normal care the wires stretched and broke. Reducing winding tension eliminated this problem, and the auxiliary coils which had no taps were successfully wound. However, one auxiliary coil required taps, and since the small connections were difficult to make with the heliarc welder, aluminum was not used in this winding.

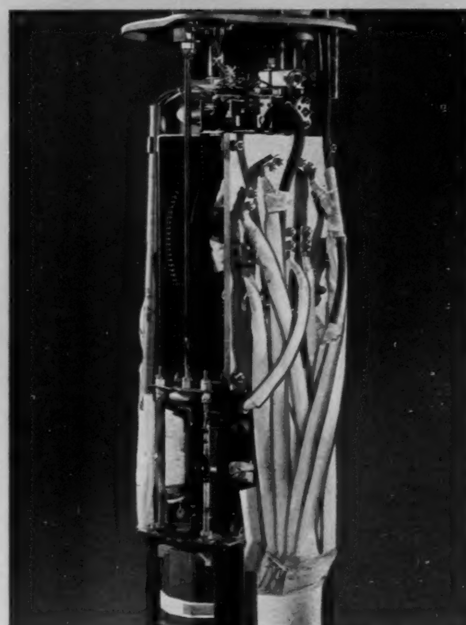
Connection problems solved

On the higher current units, preformed copper-to-aluminum connections were used. Some of these were flash welded, others pressure connected. The flash welds were made on a special machine which brings the two metals together rapidly while drawing an arc. Although the interface in the joint is thin, there is still some brittleness present. The aluminum end of this connection was heliarc welded to the aluminum tap lead, and copper brazing was used for connections to the tap changer. Figure 3 shows the tap leads between the coil and the mechanism, while Figure 4 shows the diagram for a typical regulator. The aluminum is joined to the copper inside the flexible leads.

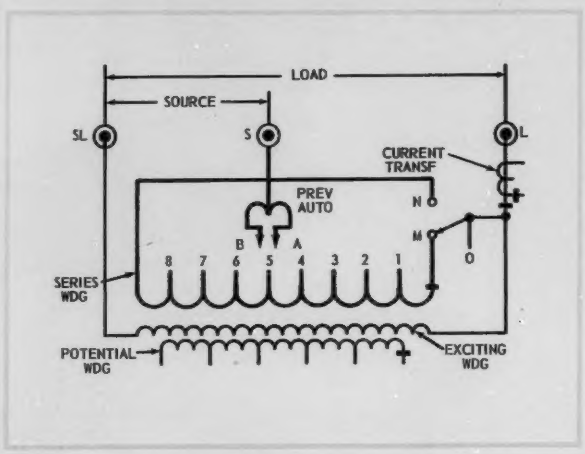
After disappointing experience with brazed or welded aluminum-to-copper joints, it was decided to use flash-welded or "Koldweld" pressure connections in subsequent units.

Research studies showed the comparable properties of these two connections. Both joints have higher tensile strength than aluminum. In bending fatigue tests the pressure connections failed in the aluminum (the joint did not fail), while the flash-welded connections failed at the interface in every instance. Resistivity of the pressure connection varied from 91 to 102 percent of the parent metals, while that of the flash weld ranged from 107 to 142 percent. Heliarc welding or copper brazing within one and a half inches of the joint did not change the conductivity of

INDIVIDUAL STRANDS are welded separately to provide a good electrical connection. **(FIGURE 2)**

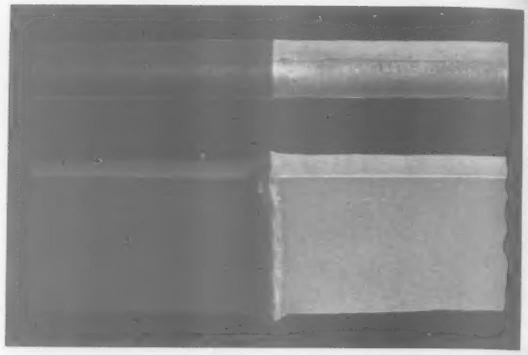


ALUMINUM is joined to copper between coil and terminals to simplify terminal arrangement. **(FIGURE 3)**



DISTRIBUTION REGULATOR diagram shows number of leads requiring aluminum-to-copper connections. **(FIG. 4)**

ALUMINUM AND COPPER CHARACTERISTICS TYPICAL DATA		
	Electrolytic Copper	**E C Aluminum**
Resistance (ratio)	1.00	1.63
Weight (ratio)	1.00	.306
Weight (equal resistance per unit length)	1.00	.50 (approx.)
Temperature Coefficient of Resistance (20 C)	0.00393	0.00403
Tens'le Strength (annealed) Psi 25 C	34,000	12,000
Cold Flow	Negligible	Appreciable above 4000 Psi



"KOLDWELD" connection between copper and aluminum (upper) is preferred. Flash weld (below) is strong but brittle. (FIGURE 5)

the pressure connection but affected its strength adversely. Such welds and brazes must be made at least four inches from the joint on a flash-welded connection.

Units proved satisfactory

Results of developmental work, investigations, and tests on aluminum units show that they are practical both electrically and mechanically.

Aluminum-wound, step-type oil-filled regulators can be made equal to copper-wound units in quality. However, copper-to-aluminum connections of the "Koldweld" type shown in Figure 5 are preferred and these connections should be located under oil. Load tap changers will be made with copper and copper alloy conducting parts.

The necessary increase in dimensions may prove somewhat of a handicap, particularly where installation will be in cubicles of limited dimensions. In pole and substation installations the aluminum-wound units should offer no problem, since space is generally available and weights will be essentially the same. Although the cost of equivalent aluminum magnet wire is generally lower than copper, heliarc welding, copper-to-aluminum connections, additional core steel and oil, and so forth, increase the overall unit cost of aluminum-wound regulators as compared to copper-wound units. As a result, at present aluminum-wound regulators are not economical, but if the cost differential between aluminum and copper continues its present trend, aluminum-wound units may not be too far in the offing.

There are vast quantities of aluminum ore available in the world, and the aluminum industry will no doubt be capable of supplying a continuing demand when conversion to aluminum-wound regulators becomes practical costwise.

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